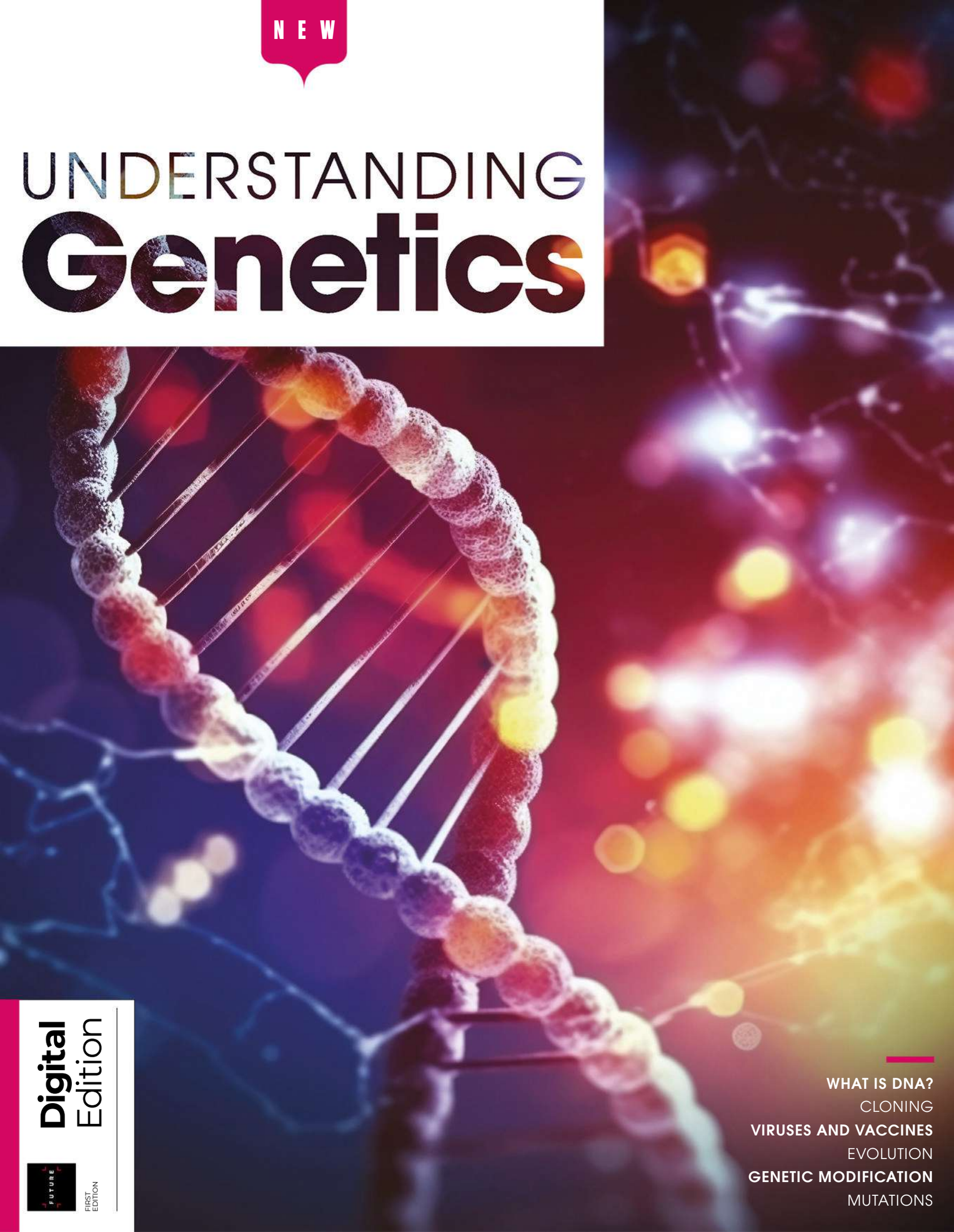
NEW

UNDERSTANDING Genetics

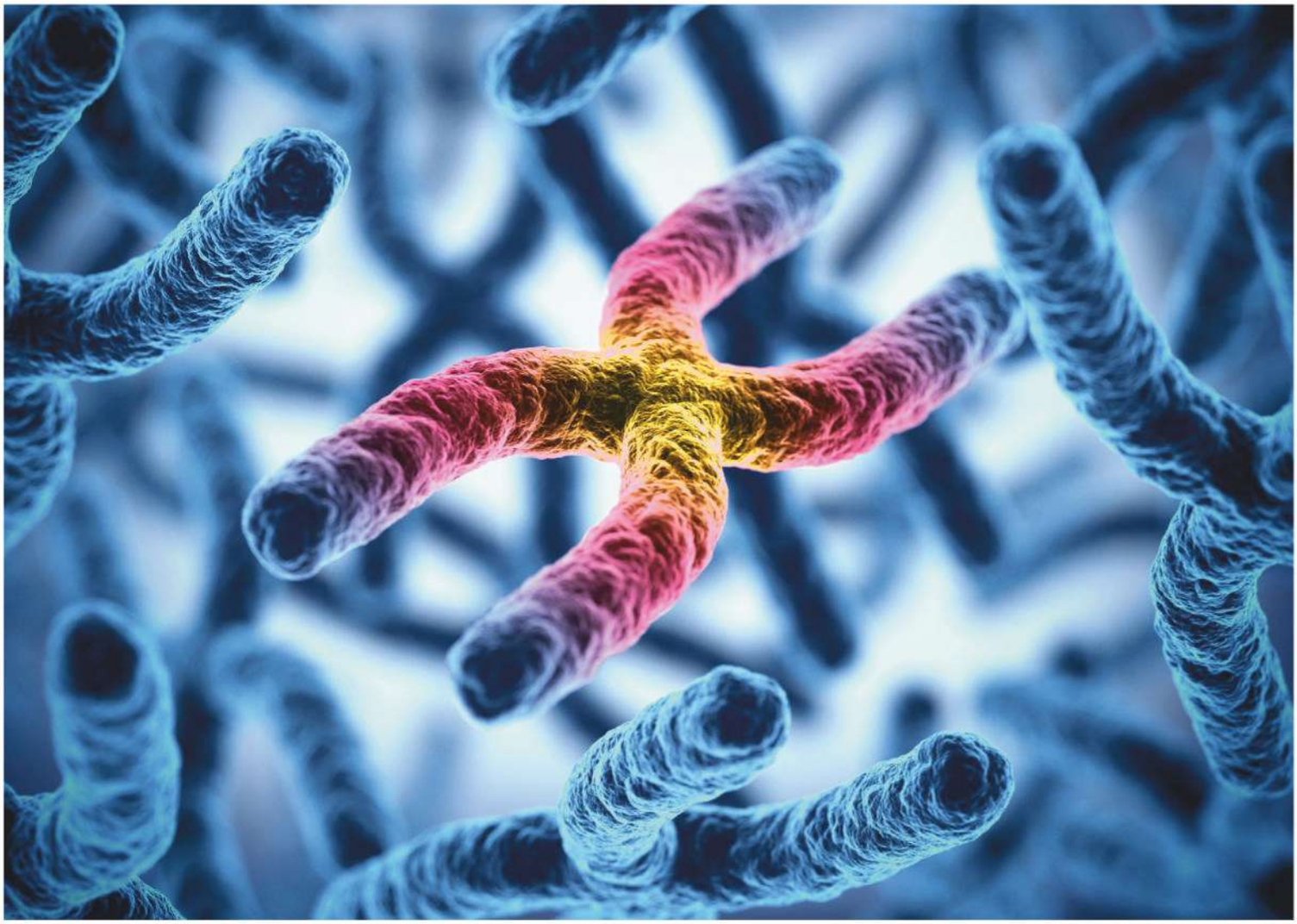


Digital Edition

FUTURE

FIRST EDITION

WHAT IS DNA?
CLONING
VIRUSES AND VACCINES
EVOLUTION
GENETIC MODIFICATION
MUTATIONS



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Welcome

The field of genetics is remarkable in that it holds the key to our past and future. Comprised of DNA sequences, our genes demonstrate how life forged pathways and evolved into the creatures and plants we know and love on Earth today.

Strings of genetic code can also hold power over us in the form of viruses, mutations leading to cancer, and more; however, we are beginning to harness genetics to fight back using remarkable leaps in genetic science, producing vaccines and powerful gene therapy.

In this bookazine, we'll take you through the world of genetics to help you understand this crucial avenue of science. Enjoy!

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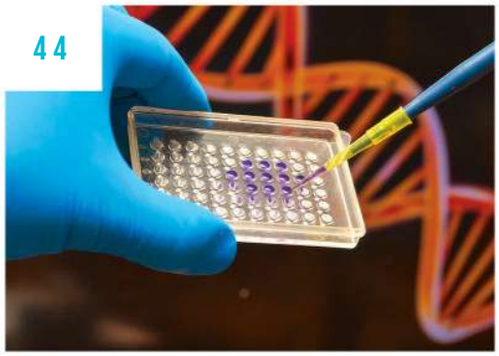

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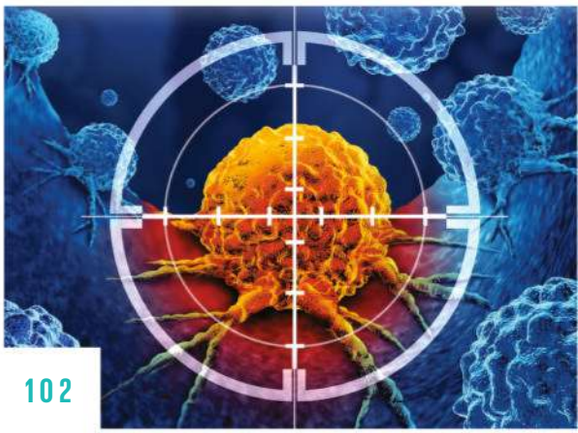

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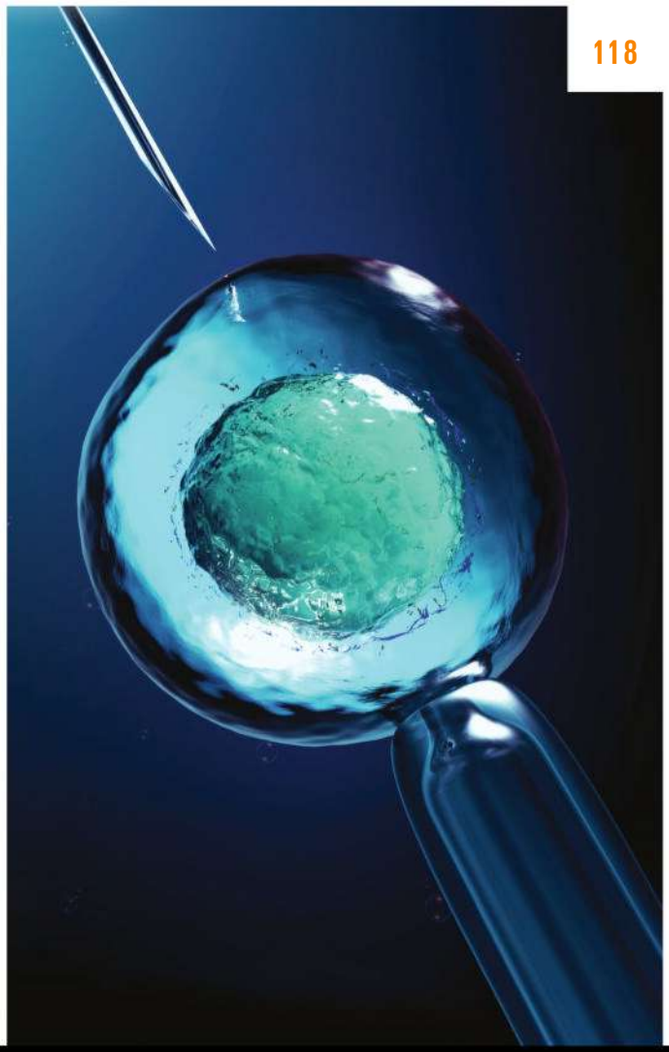

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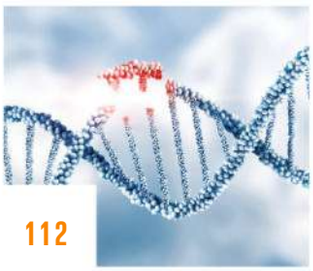

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Human Genetics

HUMAN GENETICS

Genetics

From inheritance to genetic diseases, what secrets are hidden in our genes and how do they determine who we are?

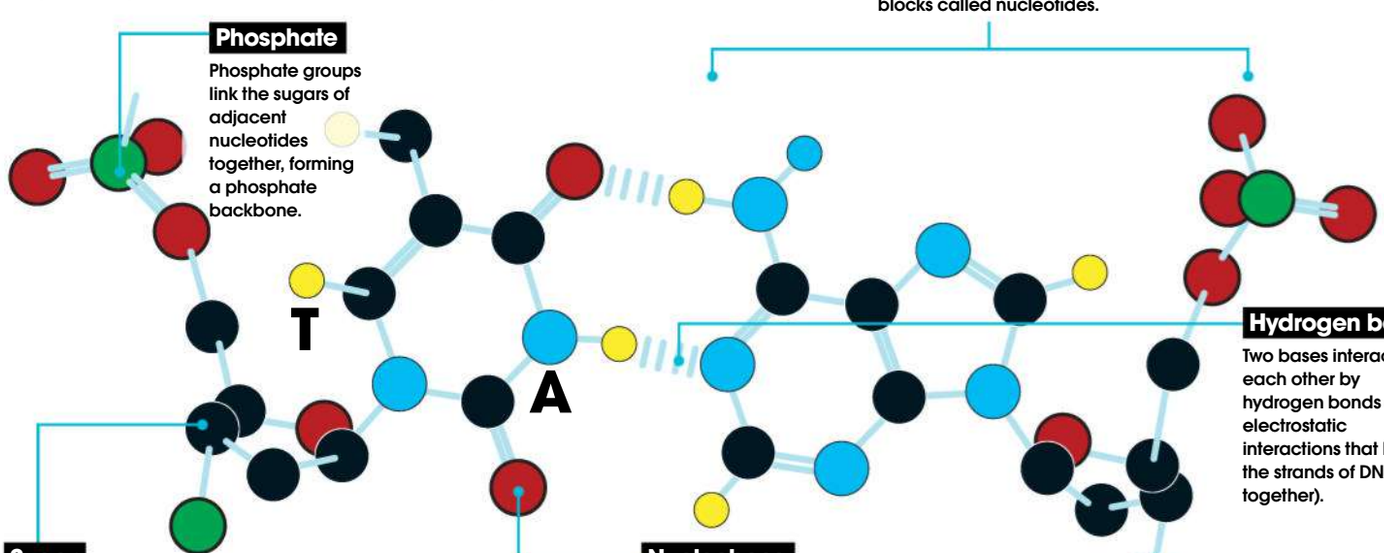
Genes define who we are. They are the basic unit of heredity, each containing a coded set of instructions to make a protein. Humans have an estimated 20,500 genes, varying in length from a few hundred to more than 2 million base pairs. They affect all aspects of our physiology, providing the code that determines our physical appearance, the biochemical reactions that occur inside our cells and even, many argue, our personalities.

Every individual has two copies of every gene – one inherited from each parent. Within the population, there are several alleles of each gene – that is, different forms of the same code, with minor alterations in the sequence. These alleles perform the same underlying function, but it's the subtle differences that make each of us unique.

Inside our cells (except red blood cells) is a nucleus, the core which contains our genetic information: deoxyribonucleic acid (DNA). DNA is a four-letter code made up of bases: adenine (A), guanine (G), cytosine (C) and thymine (T). As molecular biologist Francis Crick once explained, "DNA makes RNA, RNA makes protein and proteins make us." Our genes are stored in groups of several thousand on 23 pairs of chromosomes in the nucleus, so when a cell needs to use one particular gene, it makes a temporary copy of the sequence in the form of ribonucleic acid (RNA). This copy contains all the information required to make a protein – the building blocks of the human body.

DNA's chemical structure

We put deoxyribonucleic acid under the microscope



The Human Genome Project aimed to map the entire human genome; this map is effectively a blueprint for making a human. Using the information hidden within our genetic code, scientists have identified genes that contribute to various diseases. By logging common genetic variations in the human population, researchers have identified over 1,800 disease-associated genes, affecting illnesses ranging from breast cancer to Alzheimer's. The underlying genetic influences that affect complex diseases such as heart disease are still not yet fully understood, but having the genome available to study is making the task of identifying the genetic risk factors much easier.

Interestingly, the Human Genome Project discovered we have far fewer genes than first predicted; only two per cent of our genome codes for proteins. The remainder of the DNA is known as 'non-coding' and serves other functions. Within many human genes are non-coding regions called introns, and between genes, there is intergenic DNA. One proposed function is that these sequences act as a buffer to protect the important genetic information from mutation. Other non-coding DNA acts as switches, which helps the cell turn genes on and off at the correct times.

Genetic mutations are the source of variation in all organisms. Most genetic mutation occurs as the DNA is being copied, when cells prepare to divide. The molecular machinery responsible for duplicating DNA is prone to errors and often makes mistakes, resulting in changes to the DNA sequence. These can be as simple as accidentally substituting one base for another (for example, A for G) or can be much larger errors, like adding or deleting bases. Cells have repair machinery to correct errors as they occur and even to kill the cell if it makes a big mistake, but despite this, some errors still slip through.

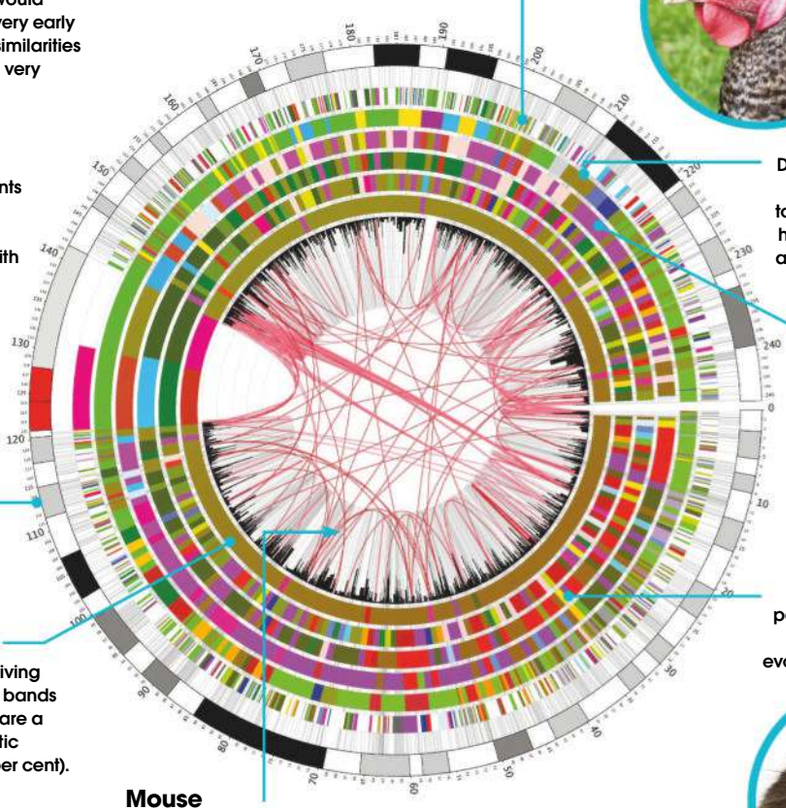
Throughout your life, you will acquire many cell mutations. Many of these are harmless, occurring in non-coding DNA regions or changing the gene so nominally that the protein is virtually unaffected. However, some mutations do lead to disease. If mutations are introduced into the sperm and egg cells, they can be passed on to the next generation. However, not all mutations are bad, and this process of randomly introduced changes in the DNA sequence provides the biological underpinning that supports Darwin's

The Human Genome Project

The Human Genome Project, an initiative to map the sequence of the entire human genetic code, began in 1990 and was completed in 2003. The 3.3-billion base pair sequence was broken into sections of around 150,000 base pairs in length, and the sequence for each was identified. These were then joined and used to map the information onto chromosomes to determine which genes were found on each – and in what order. The genome map (right) shows a human chromosome compared with other animals; the colours are a 'heat map' demonstrating areas where genetic information has been conserved through evolution (the more fragmented the pattern, the more differences there are in the genetic code).

Mapping the human genome

How does our genetic makeup compare to that of other creatures?



Zebrafish
Divergence between fish and mammals would have occurred very early in evolution, so similarities in our genes are very fragmented.

Human
This ring represents the genes on a human chromosome, with the numbers providing a representation of scale.

Chicken
Despite the fact that we are not closely related to birds, the chicken still has regions of DNA that are quite similar to ours.

Dog
Some regions of the canine genome are very different to ours, but the pink bands show an area that has been conserved.

Rat
The mouse and rat genomes have similar patterns, demonstrating these rodents' close evolutionary relationship.

Chimpanzee
One of our closest living relatives – the solid bands demonstrate we share a great deal of genetic information (ie 98 per cent).

Mouse
There is less in common between human and mouse (90 per cent), but we are sufficiently similar that mice make a good scientific model for studying human disease.

theory of evolution. This is most easily observed in animals. Take, for example, the peppered moth. Before the Industrial Revolution, the majority of these moths had white wings, enabling them to hide against light-coloured trees and lichens. A minority had a mutant gene, which gave them black wings; this made them an easy target for predators. When factories began to cover the trees in soot, the light-coloured moths struggled to hide themselves against the darker environment, so black moths flourished. They survived much longer, enabling them to pass their mutation to their offspring and altering the gene pool.

It is easy to see how a genetic change like the one that occurred in the peppered moth could give an advantage to a species, but what about genetic diseases? Even these can work to our advantage. A good example is sickle cell anaemia – a genetic disorder that's quite common in the African population. A single nucleotide mutation causes haemoglobin, the protein involved in binding oxygen in red blood cells, to misfold. Instead of forming its proper shape, the haemoglobin clumps together, causing red blood cells to deform. They then have trouble fitting through narrow capillaries and often become damaged or destroyed. However, this genetic mutation persists in the population because it has a protective effect against malaria. The malaria parasite spends part of its life cycle inside red blood cells, and when sickle cells rupture, it prevents the parasite from reproducing. Individuals with one copy of the sickle cell gene and one copy of the healthy haemoglobin gene have few symptoms of sickle cell anaemia but are protected from malaria, too, allowing them to pass the gene on to their children.

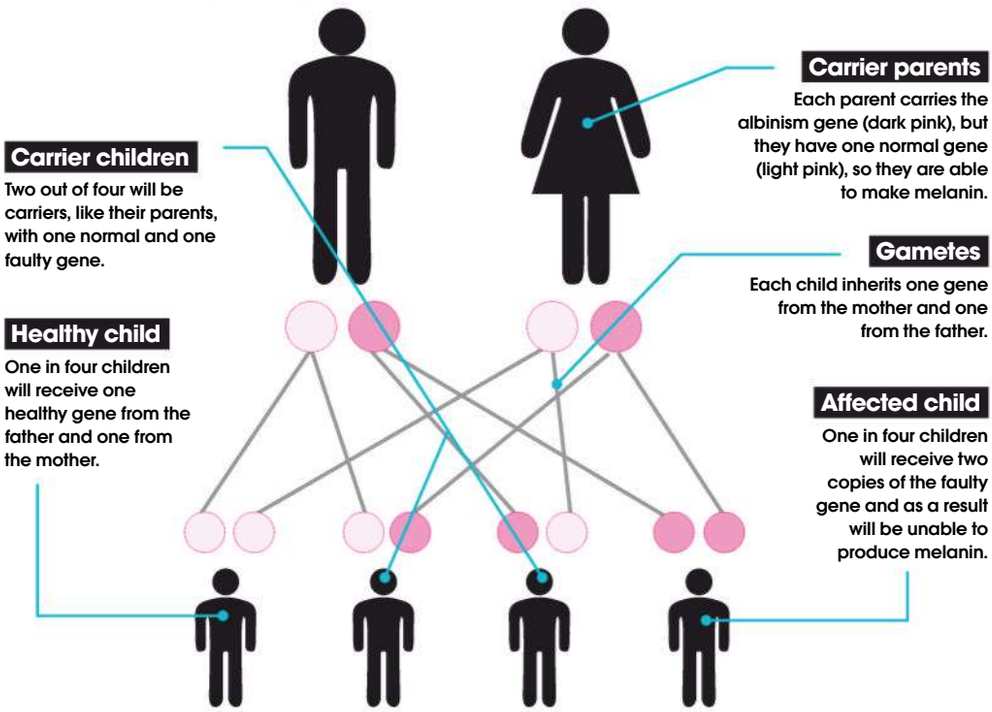
Genetics is a complex and rapidly evolving field, and more information about the function of DNA is being discovered all the time. It is now known that environmental influences can alter the way that DNA is packaged in the cell, restricting access to some genes and altering protein expression patterns. Known as epigenetics, these modifications do not alter the underlying DNA sequence, but regulate how it is accessed and used by the cell. Epigenetic changes can be passed on from one cell to its offspring and provide an additional mechanism by which genetic information can be modified across generations.

Using genetics to convict criminals

Forensic scientists can use DNA traces to identify individuals involved in criminal activity. Only about 0.1 per cent of the genome differs between individuals, so rather than sequencing the entire genome, scientists take 13 DNA regions that are known to vary between different people to create a 'DNA fingerprint'. In each of these regions, there are two to 13 nucleotides in a repeating pattern hundreds of bases long – the length varies between individuals. Small pieces of DNA – referred to as probes – are used to identify these repeats and the length of each is determined by a technique called polymerase chain reaction (PCR). The odds that two people will have the same 13-region profile is thought to be one in a billion or even less, so if all 13 regions are found to be a match, then scientists can be fairly confident that they can tie a person to a crime scene.

Why do we look like our parents?

It's a common misconception that we inherit entire features from our parents – eg "You have your father's eyes." Actually inheritance is much more complicated – several genes work together to create traits in physical appearance; even eye colour isn't just down to one gene that codes for 'blue', 'brown' or 'green', etc. The combinations of genes from both of our parents create a mixture of their traits. However, there are some examples of single genes that do dictate an obvious physical characteristic all on their own. These are known as Mendelian traits, after the scientist Gregor Mendel who studied genetic inheritance in peas in the 1800s. One such trait is albinism – the absence of pigment in the skin, hair and eyes due to a defect in the protein that makes melanin.



Did you know?
Bacteria have around 4,000 genes, yeast have 6,000, fruit flies have 13,000 and nematode worms have 18,000

The genetic revolution

From the discovery of DNA to the dawn of gene editing in less than 200 years

HUMAN GENETICS

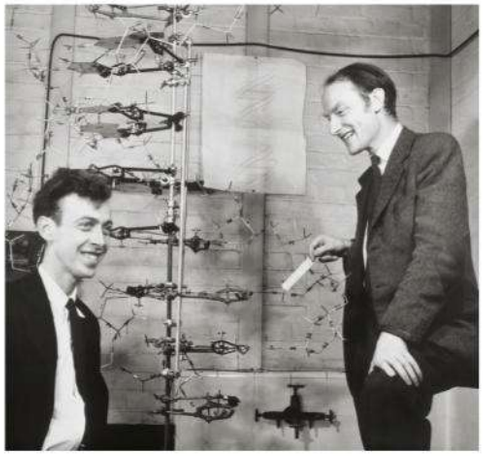
In the 1800s, Swiss biologist Friedrich Miescher discovered something strange. When he broke open the nuclei of white blood cells, he found a substance rich in phosphorous, unlike anything he'd seen before. He named it nuclein. We now know it as DNA.

DNA stands for deoxyribonucleic acid. Thanks to the work of Russian-born American scientist Phoebus Levene, we know that it has three parts. The phosphorous that Miescher noticed connects to a pentagon-shaped sugar called deoxyribose. This, in turn, links to a nitrogen-containing structure known as a 'base'. Four different bases make up the chemical letters of the genetic code, and the sugars and phosphates join them together into long strings.

The four DNA letters are adenine, cytosine, guanine and thymine. We know them most commonly by their first letter abbreviations: A, C, G and T. In a piece of DNA, the amount of A matches T and the amount of C matches G, but it wasn't until James Watson and Francis Crick that we found out why. This Nobel Prize-winning pair revealed the structure of the molecule.

Rosalind Franklin and Maurice Wilkins had taken a picture of DNA using X-rays. Using their images, along with cardboard cutouts of each of the DNA bases, Watson and Crick played with possible configurations. In 1953, they finally revealed that DNA is a double helix.

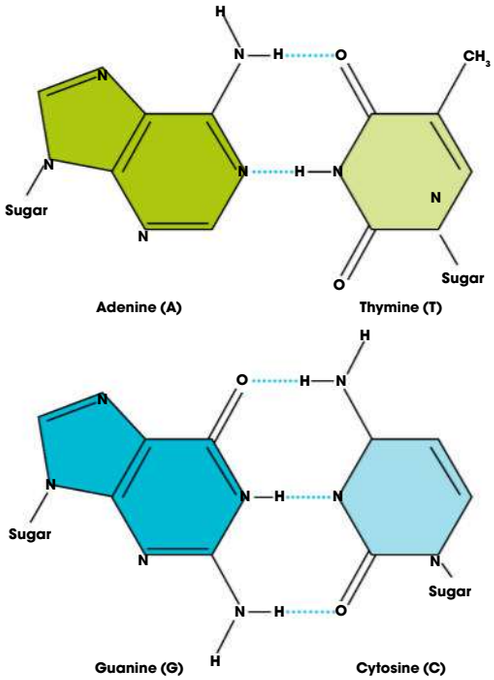
Two strands of code form a pair structured like a twisted ladder. The bases on one strand cling to the bases on another via hydrogen bonds, forming the ladder's rungs. The sugars and phosphates form the sides of the ladder, or the 'backbone'. Space between the rungs allows other molecules to read or copy the code.



Watson and Crick standing next to their famous model of the DNA double helix

DNA has a right-handed curl, and the strands store opposite sequences running in opposite directions. The As on one strip cling to the Ts on the other, while the Cs partner up with Gs. One strand stores the code running top to bottom and the other stores the inverted code running bottom to top. Each strand has an up and a down, known to scientists as the 5' (pronounced five prime) and 3' (three prime) ends. These work a bit like having a capital letter at the start of a sentence and a full stop at the end, telling the cell in which direction it should read the code.

The structure of DNA has become iconic, but the distinctive twist is a frequent chemical quirk of biological molecules. The collagen strands in your skin twist like ropes, and so does the keratin in your hair. The building blocks of DNA are asymmetrical, and they stagger when stacked end-to-end. Once Watson and Crick revealed the structure, the next step was to crack the code. The scientific cryptographer responsible was Marshall Nirenberg.



Adenine always pairs with thymine and cytosine always pairs with guanine

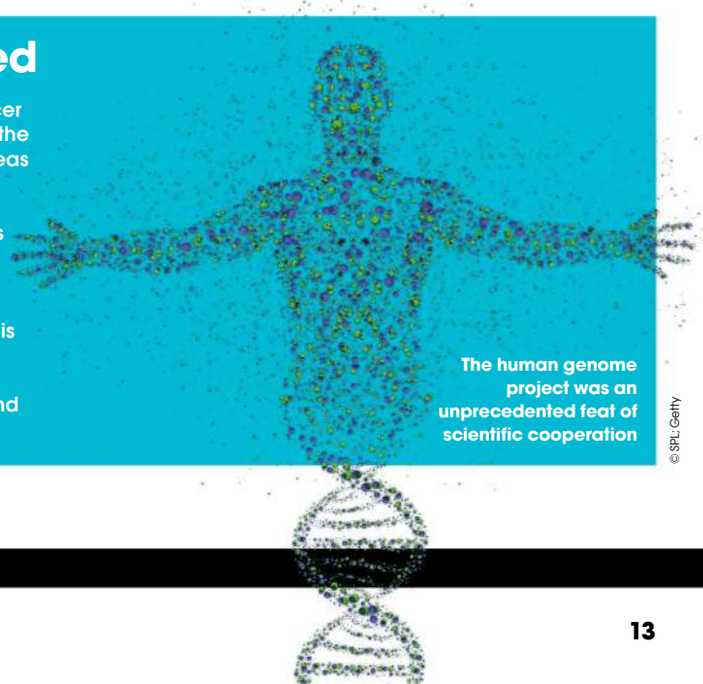
Proteins make up most of the body's molecular machinery, and cells build them from blocks called amino acids. There are 20 distinct blocks to choose from, so Nirenberg put each in a different tube. In order to understand what different DNA sequences meant, he made synthetic strings of code. Afterwards, he watched to see which amino acids would be strung together with separate sequences. His work revealed that DNA stores information as three-letter 'words'. There is a word for 'start', signalling the beginning of a gene, there are three words for 'stop', signalling the end, and, between them, there are 60 other three-letter 'codons' that correspond to amino acids.

How the human genome was sequenced

The Human Genome Project was one of the biggest scientific undertakings ever attempted. An international team of scientists worked together to read all 3.2 billion base pairs of human DNA. They mapped each human gene using a technique called bacterial artificial chromosome (BAC) sequencing.

First, they broke each chromosome into pieces around 200,000 base pairs long. Then, they slotted them into 20,000 loops of DNA. Bacteria then copied the loops, building a vast DNA library. Scientists then cut the cloned DNA into 2,000 base pair fragments. A sequencer read the fragments, and they pieced the code back together by looking for areas that overlapped.

Before the project started, people thought a genome as complicated as ours might contain more than 100,000 genes. However, when the results emerged, it became clear that there were fewer than 25,000. Armed with this knowledge, scientists continue to explore our genetic code to find out where we came from, how we work and why our bodies go wrong.



The human genome project was an unprecedented feat of scientific cooperation

© SPL; Getty

With the cipher in hand, the next step was to decode the genome. To do this, Frederick Sanger invented DNA sequencing in 1977. His pioneering technique worked by breaking the code into overlapping chunks. He then copied each chunk in the presence of 'chain-terminating' nucleotides. These stop the copying process early, indicating which base just joined the end of the sequence. Bit by bit, the process reveals each letter of the code. Once he had the sequence for each chunk, Sanger could then stitch them back together like a jigsaw.

Armed with this new tool, scientists read the first full genome in 1995. It belonged to the bacterium Haemophilus influenzae. For the first time, scientists had the full instruction manual for making a living organism. In 2000, scientists finished the genetic code of the fruit fly. In 2002, they completed the mouse. And, a year later, the holy grail of sequencing emerged: the complete human genome.

With access to these manuals, scientists could start to understand how things work and why they go wrong. By the early 2000s, they had amassed a powerful kit of molecular tools to help with their investigations. Even so, it would be an invention from two decades prior that would prove to be a pivotal piece in the mission to fully decode human DNA.

In 1983, American biochemist Kary Mullis invented a technique called polymerase chain reaction (PCR), an accomplishment for which he received the Nobel Prize in Chemistry in 1993. PCR is a DNA photocopier that can make millions of identical sequences from one DNA strand. First, the temperature rises, splitting the double helix apart. Then an enzyme called a polymerase runs along and copies the DNA. Finally, the temperature drops and the strands

Berkeley scientist Jennifer Doudna invented the CRISPR gene-editing technique

DNA's unsung heroes

James Watson and Francis Crick are world renowned for discovering the structure of DNA, but many more scientists made critical contributions to the field

1869

Finding nuclein

Friedrich Miescher found a molecule inside the cell nucleus that contained unusual quantities of phosphorous. He called the substance 'nuclein'.

1910

Nucleic acids

Albrecht Kossel spent his career studying the composition of nuclein. He discovered the five nucleic acids and received the Nobel Prize in Physiology or Medicine in 1910.

1947

Two strands

James Michael Creeth discovered how the strands of DNA stick together. He predicted that the phosphate and sugars made a backbone and the bases clung together in between.

1950

Pairs of bases

Erwin Chargaff measured the amounts of each nucleic acid in DNA. He found that there was always the same amount of A and T and C and G – they came in pairs.

1951

X-ray pioneer

William Astbury was a physicist. He was the first person to try using X-rays to solve the structure of DNA.

1952

Photo 51

Rosalind Franklin of King's College London produced the X-ray photograph that Watson and Crick used to work out the structure of DNA.

1953

From King's to Cambridge

Maurice Wilkins worked with Rosalind Franklin on the DNA X-ray images. He gave the unpublished 'photo 51' to Francis Watson in Cambridge.

1977

DNA sequencing

Two-time Nobel Prize winner Frederick Sanger is the father of DNA sequencing. He invented the 'dideoxy method', which works out the sequence one DNA letter at a time.

A revolution in gene editing

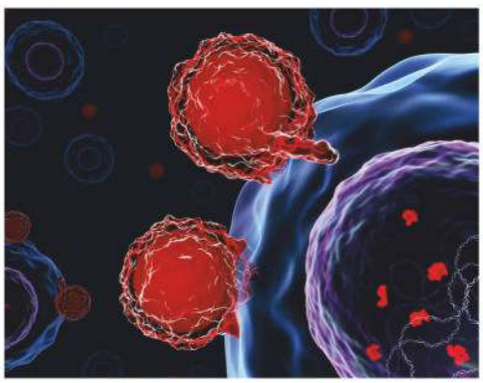
Precision gene editing with CRISPR-Cas9 could change the way we interact with our genome

CRISPR stands for 'Clustered Regularly Interspaced Short Palindromic Repeat'. The acronym describes sections of DNA that read the same forwards and backwards (palindromes). They occur in groups in some bacteria and archaea, forming part of their defence against viruses.

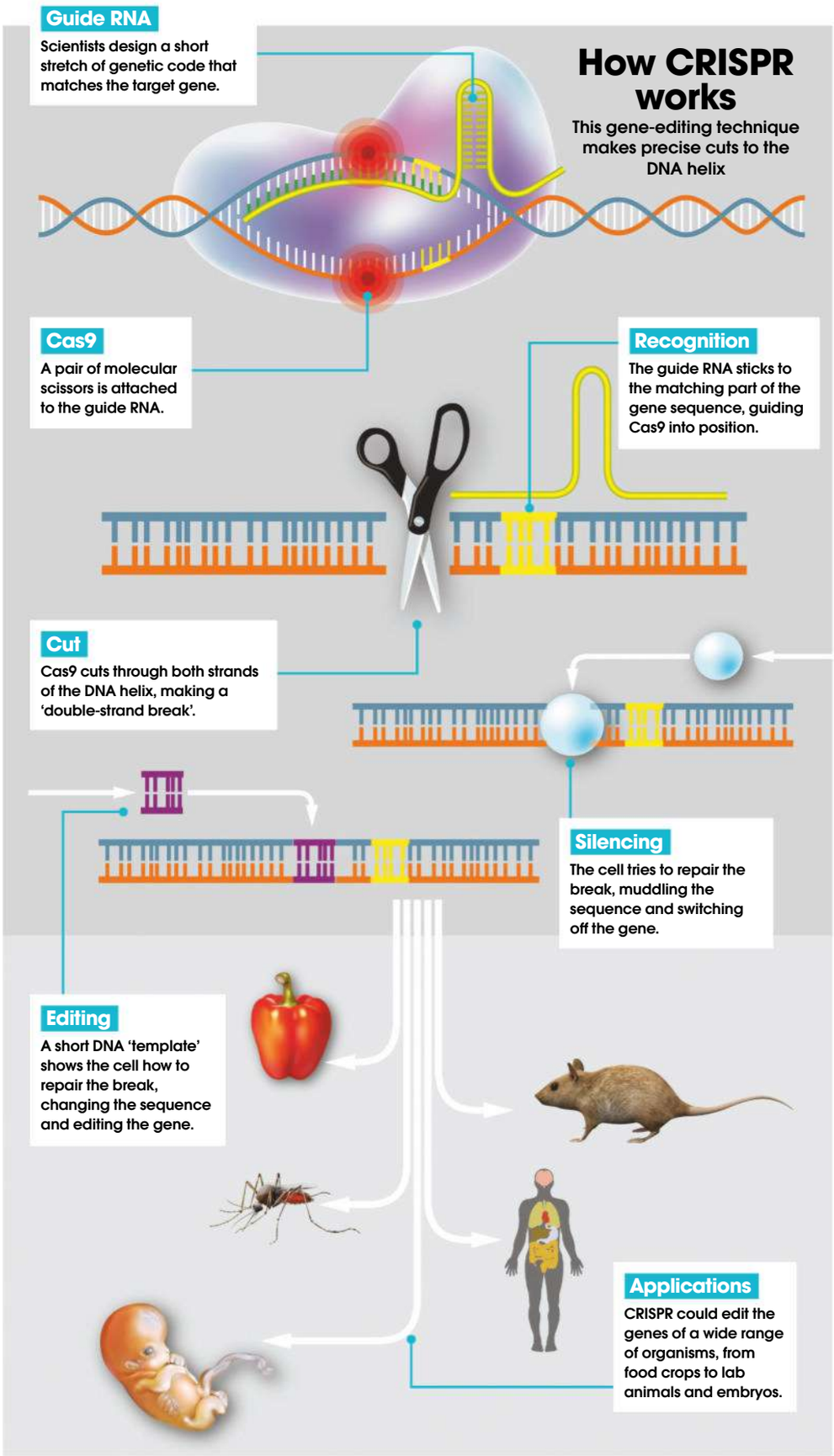
When a virus invades, the bacterium cuts out a piece of its genetic code and slots it between two CRISPR sequences. It then makes copies of the CRISPR DNA and the viral DNA sandwiched between. The copies, made from RNA, are like DNA but exist as single strands instead of double helixes. This means that the unpaired bases are free to stick to any matching code that they find inside the cell. If the same virus attacks again, the RNA sticks to its genetic code. This is where the second part of the system comes in.

CRISPR works together with molecules called Cas (which stands for CRISPR-associated). They are gene-snipping molecular scissors, and the RNA carries Cas to the matching viral genetic code, enabling Cas to cut it up. Scientists can hijack the system for genetic engineering by replacing the RNA with a sequence of their own. By designing the sequence to match part of a gene, they can guide the molecular scissors to make specific cuts in the genome.

When the cell tries to repair the cut, it often makes mistakes. This disrupts the gene, switching it off – a process known as silencing. If the scientists provide a DNA template, the cell can use it as a guide to repair the break, making edits to the gene.



CRISPR could be used to help the immune system fight cancer



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Unravelling DNA repair

In 2015, Tomas Lindahl, Paul Modrich and Aziz Sancar received the Nobel Prize in Chemistry for their work on DNA repair.

Our DNA is under assault from the environment. Ultraviolet light sticks DNA bases together and cigarette smoke causes mutations. When a cell divides, it makes copying errors. The separate work of these scientists delved into the machinery that finds this damage and fixes it. Lindahl discovered 'base excision repair', a process that cuts errors from the genome and remakes them. Sancar found a system called 'nucleotide excision repair', which removes and fixes errors that make the DNA bulge. Modrich identified DNA 'mismatch repair', which fixes areas where bases on opposite strands don't match up.

DNA damage

DNA accumulates errors over time. Some occur when cells make copying mistakes. Others are the result of an environmental attack from carcinogens like UV light, radiation or cigarette smoke.

Bases A Pairs with T C Pairs with G

Base excision repair

Chemical changes can alter the structure of bases over time. Lindahl discovered base excision repair, which cuts out the damaged areas and replaces them.

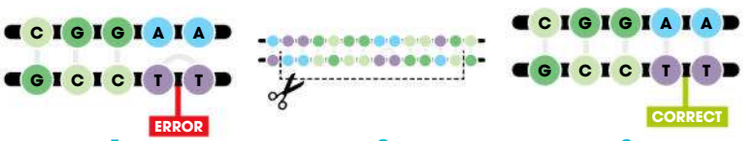
1 C loses an amino group to form U. U can't pair with G.

2 Enzymes remove U and its section of the DNA strand.

3 The correct base is inserted and the strand sealed.

Nucleotide excision repair

Environmental agents like UV light can stick adjacent bases together, forming bulges. Sancar discovered nucleotide excision repair, which recognises and repairs these errors.



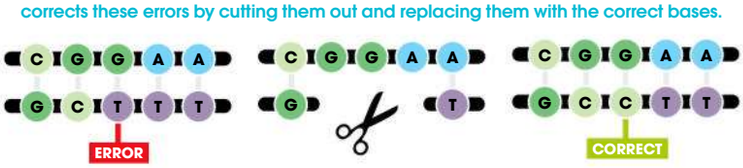
1 UV radiation can cause two Ts to bind to each other.

2 An enzyme cuts a 12-nucleotide strand, removing damage.

3 The resulting gap in the DNA is filled and then sealed.

Mismatch repair

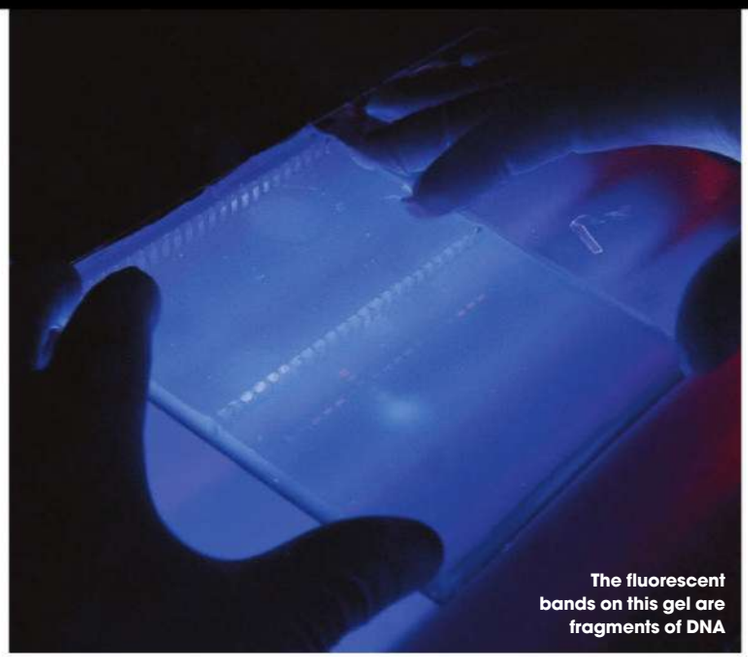
Cells make errors as they copy their genetic code. Modrich found the system that corrects these errors by cutting them out and replacing them with the correct bases.



1 Sometimes the nucleotides in copied DNA don't match.

2 Enzymes remove a section containing the faulty nucleotide.

3 The resulting gap in the DNA is filled and then sealed.

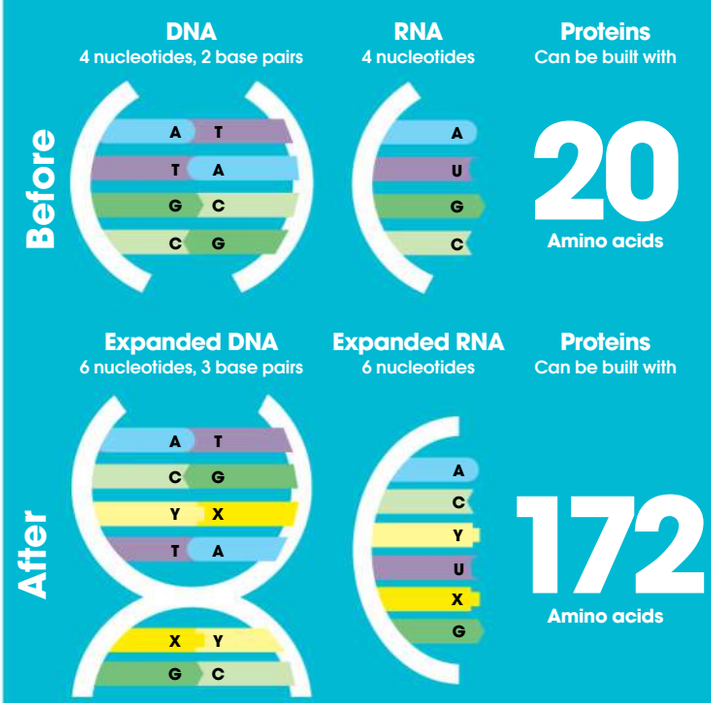


The fluorescent bands on this gel are fragments of DNA

Expanding the genetic code

In 2017, a team of scientists from California increased the size of the DNA alphabet. In 2014, they succeeded in getting E coli bacteria to put different chemical bases into their DNA. However, at the time, the extra letters were silent – they stayed in the genetic code, but they didn't spell anything useful.

Now they've upgraded the cells so they can use the code to make 'designer proteins'. In nature, cells work with a toolbox of 20 amino acids, but more exist artificially. Extra letters open up the possibility of writing new genetic words that code for these amino acids. In the latest study, bacteria put unnatural bases into their DNA. They then used the new code to add unusual amino acids to their proteins.



Scientists are trying to make designer proteins using new genetic bases and synthetic amino acids

find a matching pair to form a double helix again. Scientists can choose where to start and stop the copying process by using short stretches of DNA called primers. With this tool at their disposal, it became even easier to study individual genes.

Scientists also had access to molecular scissors called restriction enzymes. These cut DNA in specific places, often leaving a little overhang. The 'sticky ends' let scientists glue different chunks of DNA together, opening the door to genetic engineering.

Using PCR, scientists can make copies of a gene they're interested in. Then they cut open a circle of bacterial DNA, called a plasmid. They stitch the gene into place and put the plasmid back into bacteria so that the microbes can read the code. The bacteria use the gene as if it were their own, decoding the three-letter words and stringing amino acids end-to-end to make protein. The pharmaceutical industry uses this technique to make human insulin to treat diabetes, and it's widely employed in labs to manufacture protein for research. But bacteria aren't the only organisms that will accept foreign DNA. Biologists can also put genes into animal or human cells in a process called transformation.

Human cells don't use plasmids in the same way as bacteria, but there's a small chance that genetic code carried into the cell will fuse with the genome. In the early days of genetic engineering, scientists boosted the chances by making breaks in the genetic code. As the cell repaired the strand, the new DNA became a template. It worked, but it was hard to direct the genetic edits to the right place.

Then, in the 1990s, scientists discovered 'programmable nucleases'. These molecules have two parts: one sticks to specific sequences of DNA, and the other cuts through the strands. Scientists

This device is a prototype of one of the first DNA-photocopying PCR machines of the 1980s

can design stretches of DNA to match specific parts of the genome, allowing them to direct the DNA scissors to precise parts of a gene.

The first programmable nucleases were 'zinc finger nucleases'. Zinc fingers are twists of protein that recognise three base pairs of DNA, and DNA scissors can be used to shorten the sequences of bases, but they aren't always accurate. They have so-called 'off-target effects', often taking the scissors to more than one section of DNA by mistake.

The next step up was the transcription activator-like effector nucleases, or TALENs. These contain TAL effectors: proteins made by bacteria that recognise DNA. The repeats recognise one base at a time, making them more precise than zinc fingers. The latest and most exciting programmable nuclease is CRISPR, which promises precision never seen before.

With these tools at our disposal, genetic engineering is now commonplace in biomedical research. Scientists use it to switch genes on and off to study their effects. They make edits to the genomes of cells and animals, and they

"Genetic engineering is now commonplace in biomedical research"

manipulate genetic information to look for the changes that might cause disease. They put human genes into animals to see what they do; they hijack bacteria to make vast quantities of protein, and they transfer genes from one animal to another. Genes from fluorescent jellyfish proteins are used to make other animals glow, for example. Genetic engineering is also finding its way into everyday life. It gave us insulin to treat diabetes, vitamin A-rich golden rice, and soybeans resistant to weed-killers. It's now starting to make its way into medicine, too.

In the early 2000s, 13 children underwent gene therapy to repair a faulty gene that was stopping their immune systems from working. The technique cured nine of the children, but it wasn't perfect. Two went on to develop leukaemia. The repaired gene had been inserted into the wrong part of the genome, disrupting a gene involved in preventing cancer.

For genetic engineering to become a powerful clinical tool, we need more control. CRISPR promises better precision, but research is ongoing. Being able to read the genome could point to the errors that cause human disease. Being able to edit it could help us to fix them.

In the future, genetic engineering could bring us new fuels, chemicals and drugs. It could help us to increase the size of plants and animals and boost their resistance to disease. It could help endangered species to cope with changing environments or resurrect extinct animals. It might even challenge the notion of what it means to be human.

Is it right to play with our genes?

Genetic engineering is astonishing, but many people worry about the consequences. Currently, most gene editing takes place in research labs, but it could find more and more uses in the real world. One goal is to use technologies like CRISPR to repair faulty genes in the cells of sick children and adults. This might treat their illness, but the genetic changes wouldn't pass on to their offspring.

Another option is to make changes to sperm and egg cells. The genetic repairs would then be passed on to the next generation and every generation afterwards. However, making permanent changes to the human gene pool is risky.

Some people worry that we don't yet understand the human genome or the tools well enough to ensure that the edits will be safe. Others fear it's the start of a slippery slope to 'designer babies'. At present, many countries ban this type of 'germline' gene editing.

Should we use gene-editing technologies to make permanent changes to human DNA?

© Getty

Did you know?
Researchers have found over 1 million hypothetical alternatives to DNA, but no living creature uses them

DNA

Unlocking the secrets of our genetic code will make us masters of our own biology

HUMAN GENETICS

"DNA is a treasure trove of information that we're only just beginning to explore"

DNA is one of the greatest inventions of the natural world. It's a chemical library, capable of storing vast quantities of data for billions of years. Passed from one generation of flora and fauna to the next, this microscopic structure is the engine of evolution. Every living creature uses DNA as its instruction manual. The genes contained within it instruct cells how to make the proteins they need to survive, grow and reproduce.

DNA also records history, tracing the path evolution has taken to create the plants and animals we see today. Unlocking the secrets of DNA not only allows us to read our own life stories but also gives us the ability to predict – and even change – the future.

DNA is a treasure trove of information that we're only just beginning to explore. Scientists didn't even know it existed until the late 1800s, and it wasn't until the 1950s that they really started to understand how it worked. In the 1970s, scientists finally developed a technique that allowed them to read the letters of the genetic code. Suddenly, it was possible to look inside our own instruction manual and see how humans are made.

It took over ten years to complete the first map of the human genome, and the results that came out of it were a huge surprise. Scientists had predicted that it would take as many as 100,000 genes to build and maintain a human body. But the Human Genome Project revealed that we have less than a quarter of that number. Even rice plants have more genes than we do.

Today's gene sequencing technology is so advanced that machines can read off an entire human genome in a matter of hours. There are millions of individual sequences now on public record, allowing researchers to investigate the tiny genetic differences that make us who we are. These differences are the key to understanding everything from our family history and physical features to our risk of developing diseases.

At the moment, our understanding of DNA is still in its infancy, but we are standing on the precipice of a genetic revolution. Tracing our biology back to the level of our DNA will one day make it possible to customise our genetic code and even cure genetic diseases. But before we reach that point, we need to work out what every letter of that code is for.

The link between some genes and the traits they control is clear, but for most the relationship is complex. With so few genes in the human genome, it is inevitable that many have more than one role to play. Genes work together in complex and interconnected networks to shape the people we become.

To complicate matters further, genes make up only around one or two per cent of the human genome. The rest of our genetic code controls how, when and why we use our genes. How that works is mostly a mystery. Understanding gene networks – and learning to edit them – is the next step on the path to becoming masters of our own biology.

What is DNA?

Every living creature is a consequence of DNA – discover how it works here

Deoxyribonucleic Acid (DNA) is a chemical library, storing vast quantities of data for billions of years. Passed from one generation to the next, this microscopic structure is the engine of evolution. Every living creature uses DNA as its instruction manual. The genes in DNA tell cells how to make the proteins they need to survive, grow and reproduce. It may be the most famous molecule in the world, but what goes on inside that double helix? At the heart are four chemicals called nucleotides. Each contains a pentagon-shaped sugar molecule, a structure called a phosphate group and a protein fragment called a base.

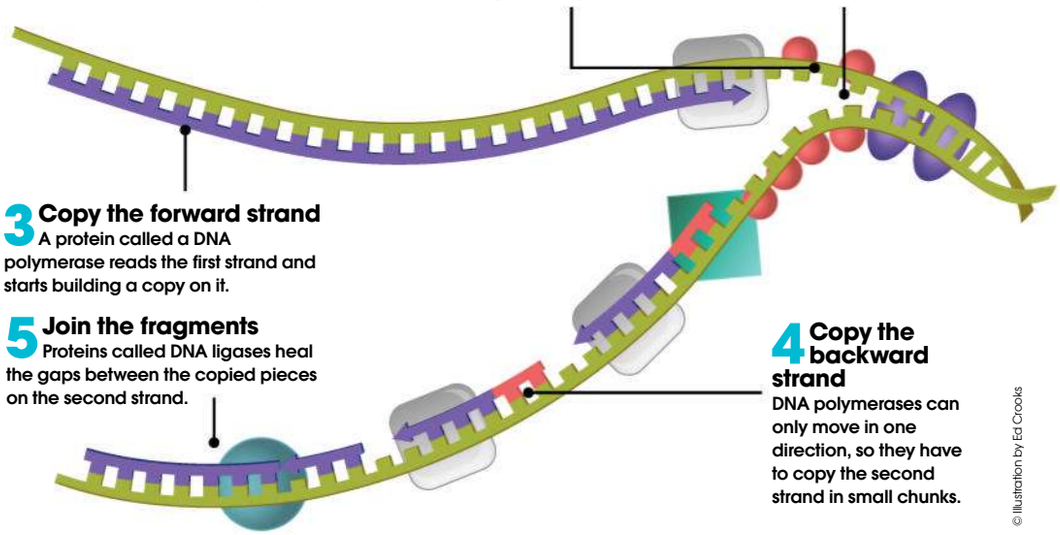
The sugar and the phosphate group are the same for every nucleotide. They join together side by side to form the backbone of each DNA strand. Like LEGO bricks, they only connect one way round; the phosphate of one nucleotide slots into the sugar of the next. This means that DNA strands have a definite 'up' and 'down'. The top is called the five prime (5') end, and the bottom is the three prime (3') end.

The two strands of a DNA helix face in opposite directions, one running five prime to three prime, and the other three prime to five prime. They twist together in a right-handed helix. If you look closely, you'll notice that the alternating twists are uneven: one big (the major groove) and one small (the minor groove).

The bases connect the two DNA strands, much like the rungs of a ladder. They form pairs, known as base pairs, linked by strong interactions called hydrogen bonds. There are four bases – adenine (A), cytosine (C), guanine (G) and thymine (T) – and they are extremely

How it replicates

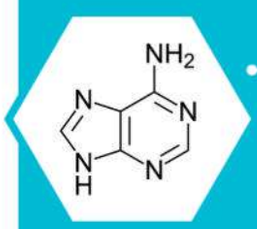
It takes an hour to turn one DNA double helix into two identical copies



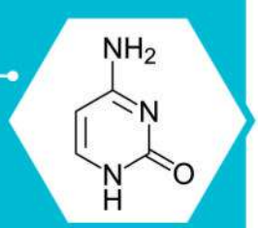
© Illustration by Ed Crooks

Four vital molecules

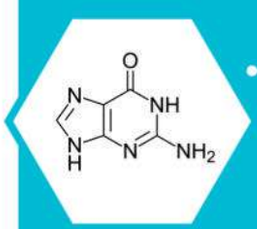
DNA's organic bases make up the most important code in the universe



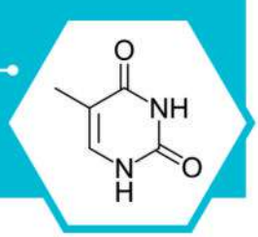
Adenine
Adenine, A for short, is a purine base. This will always pair with thymine.



Cytosine
Cytosine, C for short, is a pyrimidine base. It always pairs with guanine.



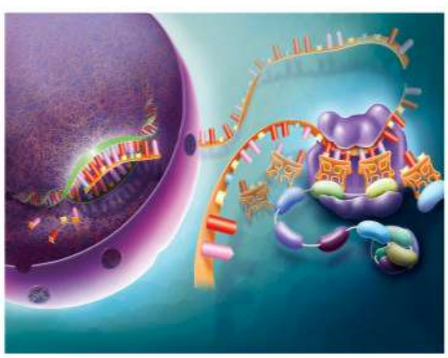
Guanine
Guanine, G for short, is a purine base. It always pairs with cytosine.



Thymine
Thymine, T for short, is a pyrimidine base. It always pairs with adenine.

What is RNA?

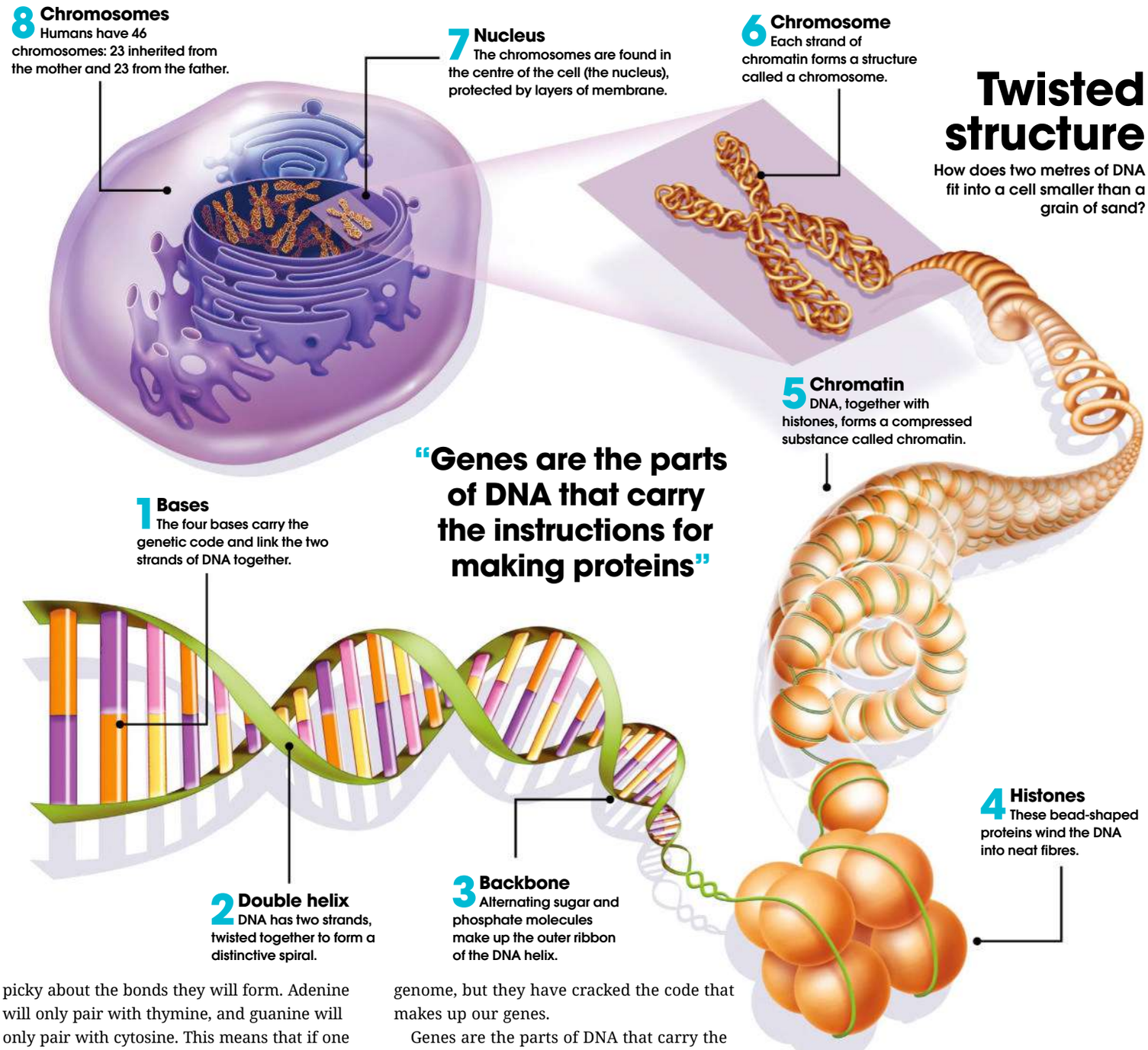
DNA is not the only genetic molecule in nature; organisms also make strands of genetic material called RNA. Chemically, the two molecules are quite similar, but they have very different roles to play. DNA forms stable double strands that carry the entire genome safely from one generation to the next. RNA forms unstable single strands that carry smaller amounts of genetic data for shorter amounts of time. Cells use RNA to make temporary copies of their genes. These copies act as templates for the molecular machines that make proteins. The machines read through the code three bases at a time, adding the corresponding amino acid to a growing protein string.



Cells copy their genes into RNA and use it as a template to make proteins

Twisted structure

How does two metres of DNA fit into a cell smaller than a grain of sand?



"Genes are the parts of DNA that carry the instructions for making proteins"

picky about the bonds they will form. Adenine will only pair with thymine, and guanine will only pair with cytosine. This means that if one strand carries the sequence ATGC, the other has to have the sequence TACG.

This strict pairing behaviour is what enables a cell to easily make copies of its genetic code. It simply unzips the two strands and then uses them both as templates to assemble two new strands, copying the matching nucleotides into the empty slots.

The most important role of DNA is to carry information from one generation to the next. This information is written in code, using the four bases as chemical letters. Scientists have yet to decode the meaning of the entire human genome, but they have cracked the code that makes up our genes.

Genes are the parts of DNA that carry the instructions for making proteins: the molecules that build our bodies and do the hard biochemical work that keeps us alive.

The building blocks of proteins are amino acids, and there are 20 different types of amino acid to choose from. The order of amino acid in a protein dictates how the protein folds up to form a 3D structure and how it behaves inside the body.

The instructions for building proteins are written into our genes as strings of three-letter words called codons. It is possible to make 64 three-letter words using the four DNA bases. This means that, just like in English, some genetic words have the same meaning.

The codon ATG means 'start', signalling that the instructions to build a protein begin here. The codons TAA, TAG and TGA mean 'stop', signalling that the protein ends here. The rest correspond to different amino acids. Cells copy the genes they want to use and read through the codons one by one, selecting the matching amino acid and connecting it to a growing string. When they reach a stop codon, they know that the string is complete, and the protein is ready to fold into its 3D shape.

© Getty, Alamy

History of DNA

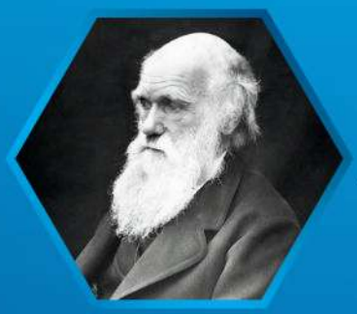
How we've come to understand more about it since its discovery

Mitosis explained

How does one cell split into two identical copies of itself?

5 Interphase
The chromosomes unfurl, allowing the cell to use and copy its genes.

4 Telophase
A new nucleus forms around each set of chromosomes, and the cell splits in two.



Source: Wiki/Leonard Darwin

1859

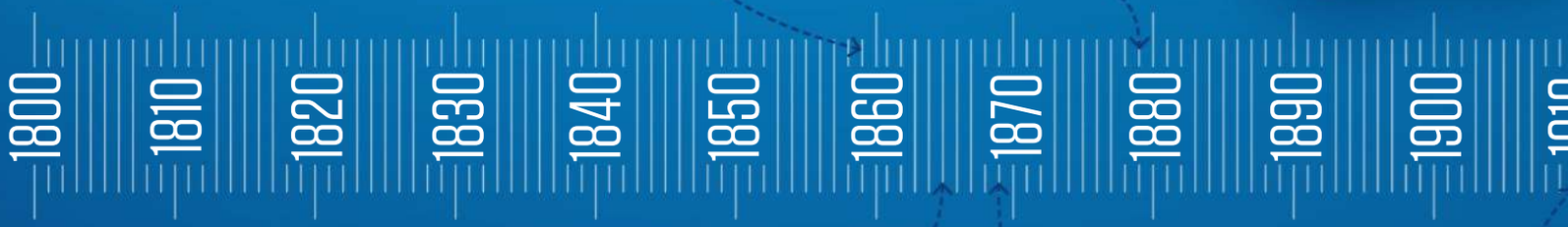
Charles Darwin publishes On the Origin of Species, describing how life evolves through natural selection.

1879

Walther Flemming

Flemming becomes the first person to observe cell division, or 'mitosis'. He dyes salamander DNA with a chemical called aniline. He then watches as the chromosomes in the nuclei turn into thick threads, which line up across the middle of the cell. The threads then separate into two groups, and the cell splits in half.

> "They base their breakthrough on the work of dozens of other scientists"



1865

Gregor Mendel

Mendel, a monk, presents his work on dominant and recessive genes after performing experiments on nearly 30,000 pea plants. He cross-pollinates pea plants to find out how traits like colour and texture pass from one generation to the next. He discovers that some traits always pass from parent to offspring, while others sometimes seem to skip a generation.

Source: Wiki/Unknown Author

Source: Wiki/TBD

1869

Friedrich Miescher

Miescher finds a strange substance while examining the pus inside used bandages. Pus contains white blood cells, and inside their nuclei, Miescher discovers a chemical that contains phosphorous and nitrogen. He names it 'nuclein'. The substance is part protein, part acid, so scientists later rename it 'nucleic acid'.

Mendel's Peas

Parent generation

Mendel starts his experiment with two pure-bred peas: a smooth variety and a wrinkly variety. The gene that determines texture has two variants, known as 'alleles'.

F1 generation

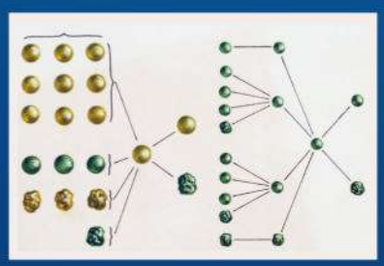
When Mendel crosses the pea plants, they inherit one allele from each parent: a smooth allele and a wrinkly allele. The smooth allele is 'dominant', so all the peas are smooth.

F2 generation

When Mendel crosses these plants, 25 per cent inherit two smooth alleles, 25 per cent inherit two wrinkly alleles and the rest inherit one of each.

Recessive genes

The wrinkly allele is 'recessive', which means that the peas have to have two copies of it to end up with wrinkly skin. Peas with one smooth allele always end up smooth.

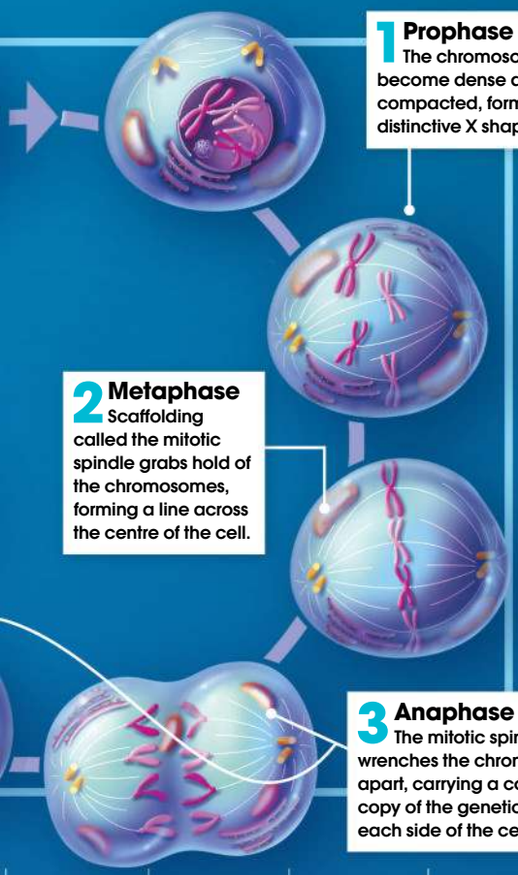


Mendel discovered dominant and recessive genes by crossbreeding pea plants

1910

Albrecht Kossel

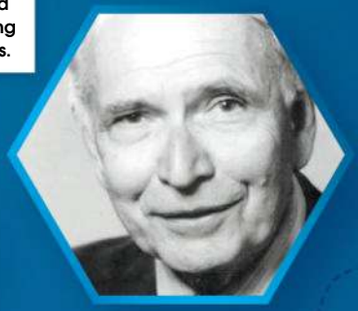
Kossel receives a Nobel Prize for discovering nucleic acids. He works together with his students to analyse the chemical components of nuclein, discovered by Miescher. They find that this strange chemical contains five types of nucleic acid: adenine, cytosine, guanine, thymine and uracil. The first four are the bases that make up DNA.



1 Prophase
The chromosomes become dense and compacted, forming distinctive X shapes.

2 Metaphase
Scaffolding called the mitotic spindle grabs hold of the chromosomes, forming a line across the centre of the cell.

3 Anaphase
The mitotic spindle wrenches the chromosomes apart, carrying a complete copy of the genetic code to each side of the cell.



Source: Wiki/US National Academy of Sciences

1953

Francis Crick & James Watson

Crick and Watson solve the structure of DNA, revealing a ladder of bases surrounded by two ribbons of phosphates and sugars. They base their breakthrough on the work of other scientists, crucially Rosalind Franklin. Using Photo 51 for reference, they construct 3D models of DNA. They know from the work of Chargaff that bases come in pairs, and from the work of Linus Pauling that bonds between specific chemicals stick out at specific angles. At first they get the shape of thymine and guanine wrong, which makes fitting the pieces impossible. When Jerry Donohue suggests a different layout, the parts finally slot into place.

1950

Erwin Chargaff publishes his work on bases. He notices that DNA contains equal amounts of adenine and thymine and equal amounts of guanine and cytosine.

1959

Severo Ochoa and Arthur Kornberg receive a Nobel Prize for working out how cells make DNA.

1961

Marshall Nirenberg cracks the genetic code, working out how the letters correspond to the building blocks of proteins.

1977

Frederick Sanger invents Sanger sequencing, a way to read the letters of the genetic code.

1996

Scientists in the UK become the first to clone a mammal from an adult cell: Dolly the sheep.

2003

An international team publishes the first complete map of the human genome.

1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020

Source: Wiki/UnknownAuthor

1919

Phoebus Levene publishes his 'polynucleotide model', suggesting that DNA is a string of four types of nucleic acid.

1952

Maurice Wilkins

After working on radar during World War II, Wilkins moves to King's College London to capture images of DNA. Working together with graduate student Ray Gosling and biophysicist Rosalind Franklin, he uses X-rays to photograph the genetic code. He shares one of Franklin's photographs with Watson and Crick in Cambridge.

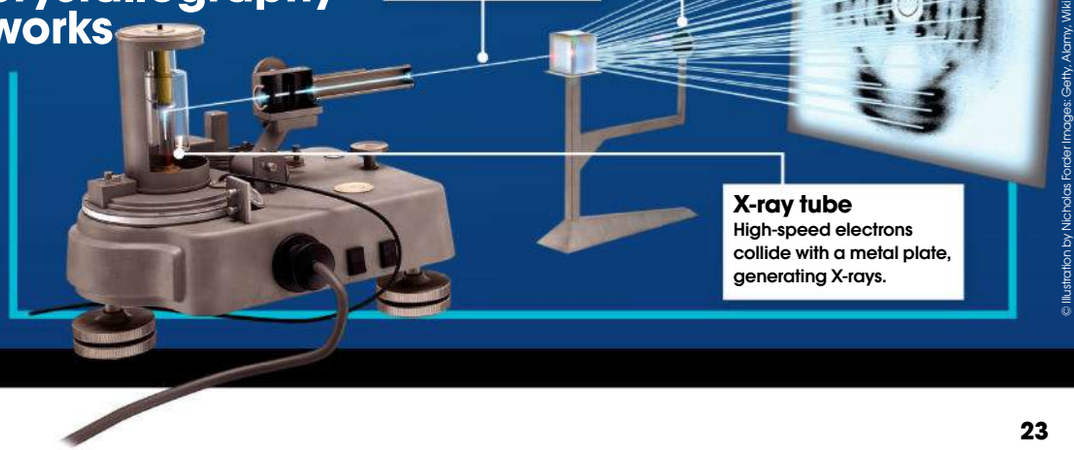
Source: Wiki/Laboratory of Molecular Biology

1952

Rosalind Franklin

Franklin captures Photo 51, revealing the helix shape of the DNA molecule. Her clear and striking photograph is instrumental in deciphering the structure of DNA, although James Watson doesn't acknowledge that until after her death from ovarian cancer in 1958. Crick, Watson and Wilkins receive the Nobel Prize for the discovery of the structure of DNA four years later.

How x-ray crystallography works

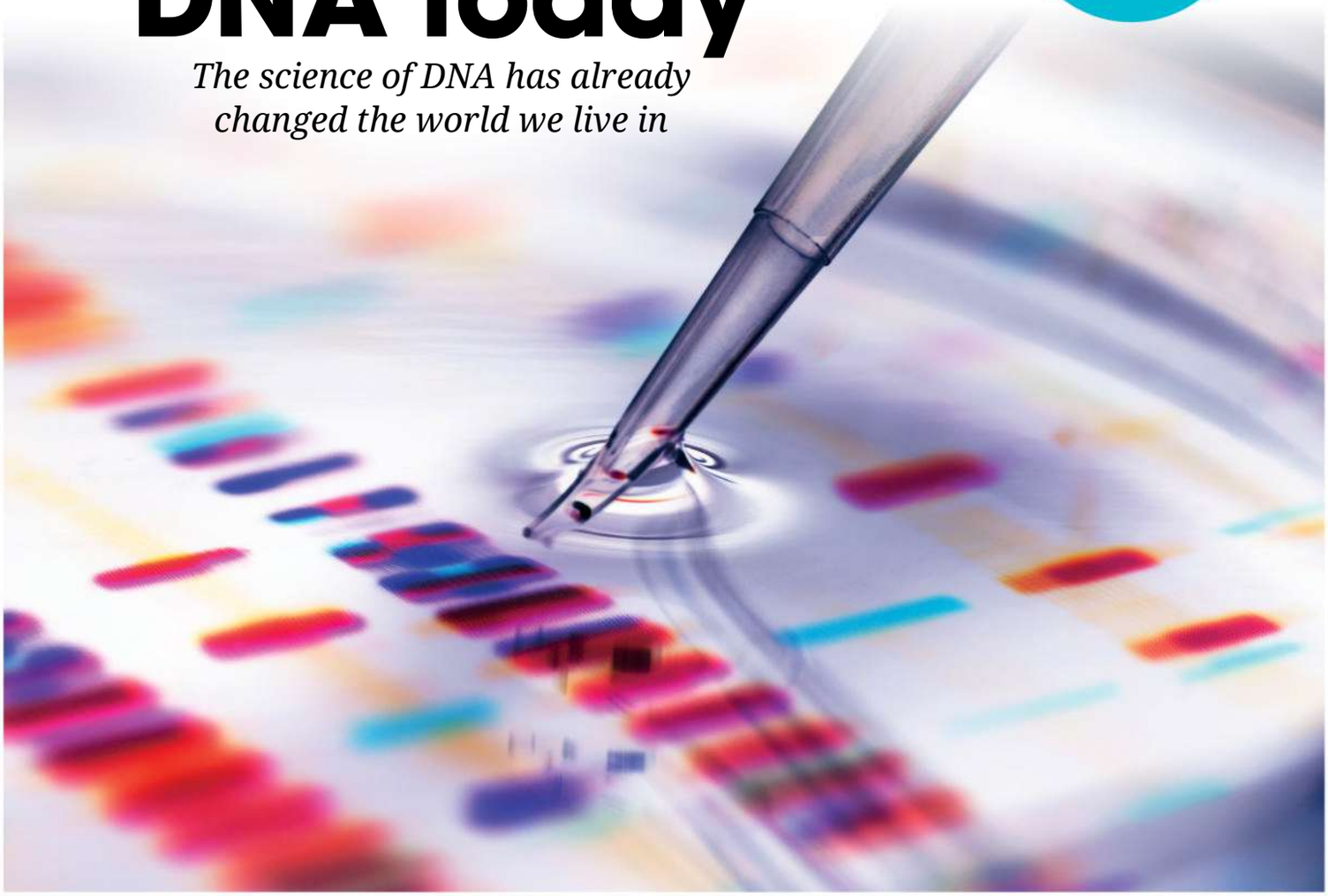


© Illustration by Nicholas Forder Images: Getty, Alamy, Wiki

Did you know?
The plant Paris japonica has the longest genome ever sequenced: a whopping 149 billion base pairs

DNA today

The science of DNA has already changed the world we live in



Taking samples

Cells and fluids taken in different ways hold the key to your unique genetic identity

Cheek swab
Gently rubbing the inside of the cheek removes the top layer of skin cells, providing enough DNA for testing.

Blood test
Red blood cells don't contain DNA, so blood tests look at the genes in white blood cells.

Saliva sample
Saliva contains cells from the cheeks, making spit samples an easy way to collect DNA at home.

Heel prick
Tiny blood samples taken when babies are just a few days old can reveal problems in the blood caused by genetic conditions.

DNA testing can help to reveal the identity of unknown human remains

Archaeology

Rebuilding history

Skeletal remains can contain traces of ancient DNA for thousands of years. Extracting and sequencing this genetic material can reveal not only the sex of the individual but also their ethnicity. This can help to retrace the steps taken by our ancestors as they spread across the world.

Forensics

Solving crimes

Forensic scientists identify DNA by examining sequences called 'short tandem repeats'. These sequences occur in the gaps between genes and contain three or four DNA letters, repeated a different number of times in different people. Scientists count the number of repeats and compare them to repeats in a suspect's DNA.

Paternity

Identifying fathers

Children inherit half of their genes from their mother and half from their father. In a paternity test, scientists compare around 15 genes from the mother, child and potential father to see how similar they are. Statistical analysis gives a score called a 'combined paternity index' – the likelihood of the person tested being the father.

Genetic heritage (ancestry)

Estimating ethnicity

Ancestry is written into DNA like a fingerprint. Different populations of humans, separated by geography, develop their own unique mutations. These pass along from one generation to the next, leaving traces in genetic code. Comparing a genome against thousands of others can reveal where a person's ancestors came from.

Gene therapy

Repairing genes

A handful of gene therapies are now licensed for use in human patients. These cutting-edge treatments use harmless viruses to carry healthy human genes into cells with genetic faults. The viruses paste these healthy genes into human DNA, fixing rare genetic disorders or killing cancer cells.

Personalised medicine

Medicine for you

Tiny differences in our genes change the way illnesses affect us. A tumour might shrink in response to chemotherapy in one patient and not respond at all in another. Genetic testing can reveal which drugs might work best for which person, allowing doctors to match treatments to patients based on their unique genetic make-up.

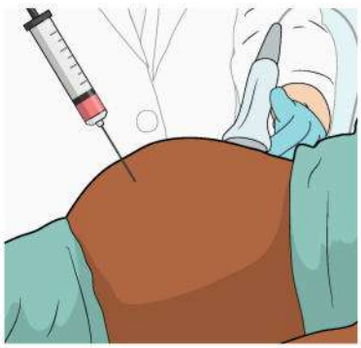
Genetic engineering can make plants resistant to pests and climate change

Gently swabbing the cheek dislodges enough cells for a DNA sample

The future of DNA science

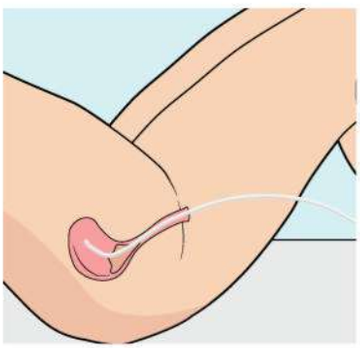
Over the next century, advances in DNA science are set to change the world forever. Armed with hundreds of thousands of unique human genome sequences, scientists are now working on the painstaking task of deciphering our genetic code. Understanding how each section of sequence controls the traits we inherit could lead to breakthroughs across dozens of different fields. It will tell us how we evolved, why we get sick and what happens as we age. As genetic engineering improves, we will gain the power to repair, edit and even rewrite our genes. Research scientists can already change the genes of laboratory animals, editing the letters to erase dangerous mutations and to enhance the traits that nature evolved on its own. As these techniques become safer, and as our understanding of our own genetics grows, we will gradually gain the power to change the genetic destiny of our species.

"We will gain the power to repair, edit and rewrite our genes"



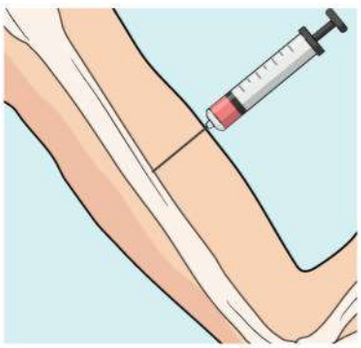
Amniocentesis

Amniotic fluid contains skin cells from a developing baby. Extracting a small sample allows doctors to test for genetic conditions.



Chorionic villus sampling

The placenta is genetically identical to the developing foetus. Cells from the placenta can reveal genetic conditions early in pregnancy.



Fine needle aspiration

Extracting a small number of cells from inside the body can reveal genetic changes in diseases like cancer.

These mice have a jellyfish gene that makes their skin and hair glow green

© Illustrations by Ed Crooks Images: Getty

What are microRNAs?

The 'junk DNA' that controls at least 30 per cent of our genes

When scientists sequenced the human genome, they expected to find hundreds of thousands of genes. As it turned out, we only have approximately 25,000, and most of the rest of our genetic code is 'junk'. Or so we thought.

Genes are sections of genetic code that carry the instructions to build proteins; effectively, they are the instruction manual for the human body. When cells want to make a protein, they make lots of temporary copies of its gene. These copies pass out of the cell nucleus and into molecular machines, which read the sequence and assemble the protein. For the cell to work properly, getting the timing right is crucial.

When the cell wants to turn production off, it could simply stop making copies of the gene, but old copies hang around in the cell and can carry on making proteins. This is where microRNAs (miRNAs) come in. These short stretches of genetic code come from the 'junk' part of our genome. There are around 2,200 of them, and they fine-tune protein production.

As with normal genes, the cell makes temporary copies of its code, but these copies don't tell the machines to make protein. Instead, they stick to the copies of protein-coding genes and stop them from passing through the machinery. They also 'tag' copies for destruction, telling the cell to remove the unwanted code. miRNAs keep production in check, ensuring cells have the right amount of protein at the right time.

The links between miRNA and disease

Our cells are like finely tuned machines; changing the levels of different proteins can completely change their behaviour. By interfering with protein production, microRNAs help to control critical cell activities, like metabolism, development and cell death. However, if the balance isn't right, this can lead to disease.

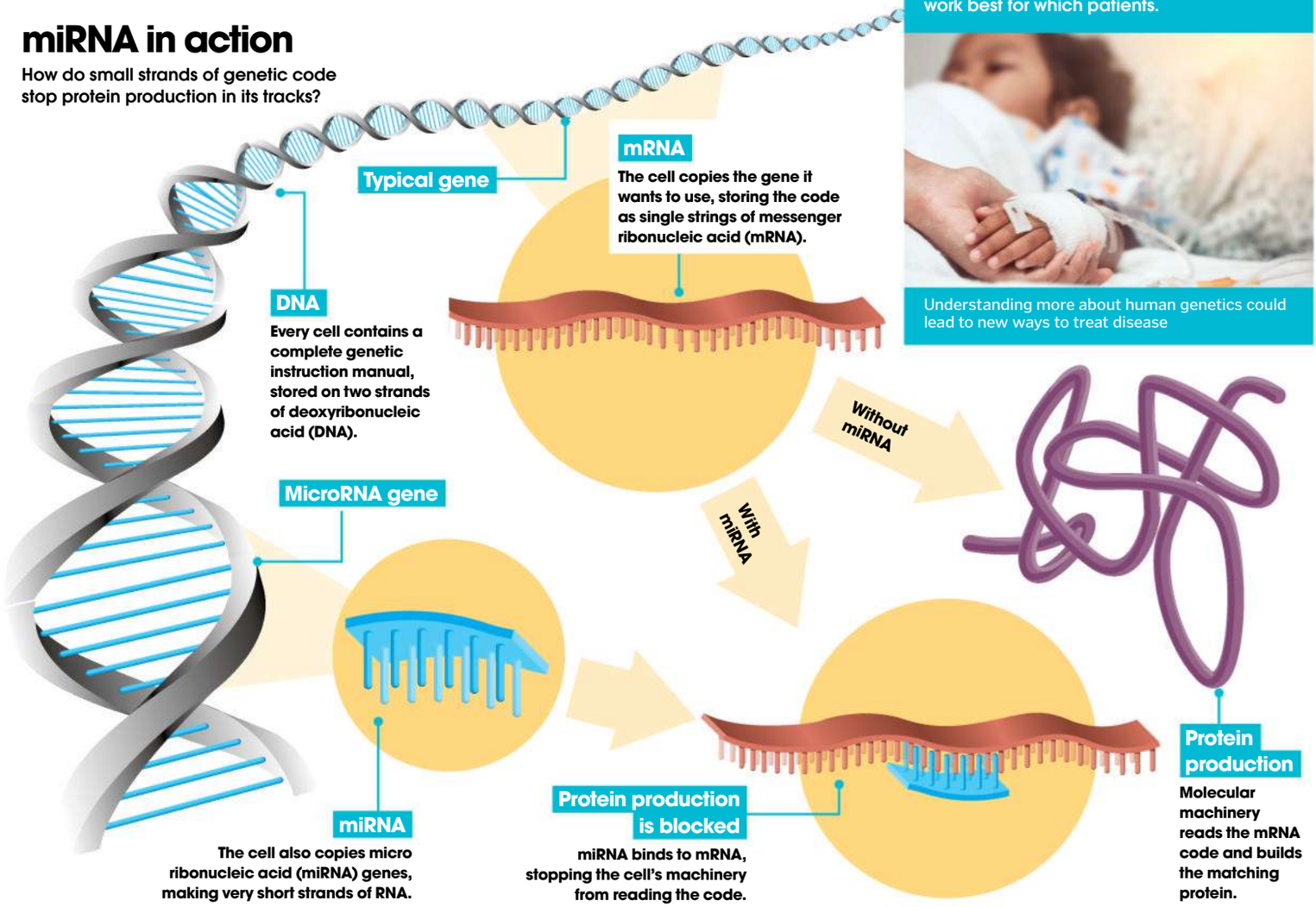
Scientists have discovered that patterns of miRNAs change in certain types of cancer, and this may affect how tumours develop. miRNAs also seem to be important in heart disease, neurological diseases and the immune system.

In the future, testing miRNA levels could help doctors to make faster, more accurate diagnoses. They could even reveal clues about which treatments might work best for which patients.

Understanding more about human genetics could lead to new ways to treat disease

miRNA in action

How do small strands of genetic code stop protein production in its tracks?



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How babies are made

The fusion of sex cells that begins the great journey of pregnancy

HUMAN GENETICS

Humans reproduce by sexual reproduction. This mixes the genetic information of two people. For this to happen we have evolved specialised sex cells, known as gametes, that are specific to each sex. Females produce and carry egg cells that, much like their vastly larger avian equivalents, contain both genetic information and form the nexus of an embryo. Females also have a dedicated sex organ called a uterus, which nurtures the embryo during its development. Males provide the other half of the genetic information by producing sperm cells.

Both the egg and sperm hold instructions encoded by deoxyribonucleic acid (DNA), which contains all the information needed to form a functional human body. The cells' DNA is wrapped up tightly into large structures called chromosomes. Both the egg cell and the sperm cell carry 23 chromosomes, which once aligned in an embryo, will form 23 pairs that will be carried by every somatic cell in a mature human body. Two of these chromosomes form a pair known as sex chromosomes, as they define the baby's sex during development. Every egg cell carries an X chromosome, and a sperm cell can carry either an X or a Y chromosome. Females are encoded by a combination of XX, and males by a combination of XY. Our genetic sex is sealed the moment our two sets of chromosomes meet during fertilisation.

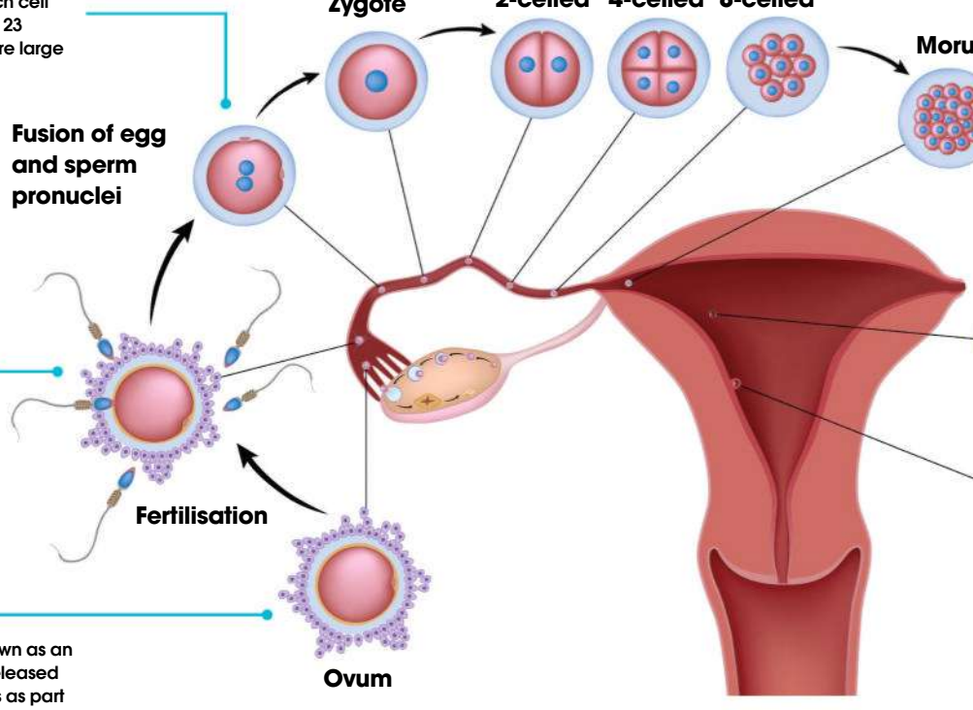
Fertilisation can begin once an egg is released by a follicle in the ovaries, a step that occurs periodically in women of fertile age. Throughout this cycle, stages of hormones trigger the release of an egg, which in turn triggers more signals intended for the wall of the uterus, which thickens in expectation of a fertilised embryo to implant on its surface. This offers a brief window of time for legions of sperm to be released from a male's testicles and undertake the long, arduous journey through a female's uterus to reach the egg while it is viable.

The fusion between a sperm and egg cell's DNA marks the beginning of embryo development, and once it has found its home in the nourishing lining of the uterine wall, the embryo undergoes a monumental growth spurt. It transforms from a mere bundle of cells into a foetus, acquiring a heart, brain, jaw, fingers and toes. Within the first 12 weeks of pregnancy, the foetus boasts a full complement of organs. This incredible metamorphosis is guided on a cellular level by genetic instructions encoded within the DNA and by external environmental signals. These signals tell the cells how to interact with one another, where to migrate, how to divide and when to die to make way for new cells. This allows a swarm of microscopic cells to differentiate and develop into something not only gargantuan in size but also in complexity: a fully formed human baby.

A sperm cell must pass a thick membrane encasing the egg, known as a zona pellucida, before fertilisation can occur

The genesis of life

The steps that bring together DNA from parents and initiate pregnancy



Union
A fertilised cell with a full complement of 23 pairs of chromosomes forms a zygote, which migrates through the fallopian tube towards the uterus.

Cleavage
As the fertilised cell migrates towards the uterus it undergoes cleavage, dividing from a single cell into a connected cluster of cells called blastomeres.

Morula
The berry-like configuration of blastomeres continues to divide, becoming a morula. During these latter divisions, the cells commit to becoming either the embryo or placenta.

X meets Y, or X
Following fertilisation, the two cells combine their DNA. Each cell carries a single copy of 23 chromosomes, which are large packages of DNA.

Fertilisation
For 12 to 24 hours after it's released, an egg can be fertilised by a sperm cell that has successfully traversed the fallopian tube.

Ovulation
A mature egg cell, known as an ovum, is periodically released from a female's ovaries as part of the menstrual cycle.

Blastocyst
A cavity of fluid builds between the inner cell mass, which will become the embryo, and the outer cells, which will help form the nourishing placenta.

Implantation
The blastocyst adheres to the wall of the uterus, known as the endometrium, which helps nourish the embryo throughout its development.

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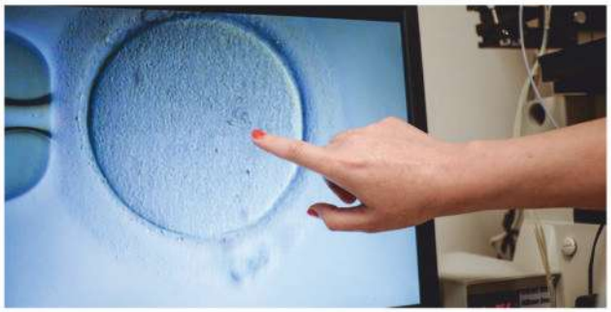
In Vitro Fertilisation

How embryos can be created in a lab

The process of fertilisation and embryo implantation is a wonderfully elegant yet complex process. This complexity, however, presents numerous opportunities for natural obstacles and barriers that prevent natural conception. Such obstacles include damage or blockage of the fallopian tubes, which can prevent the sperm and egg from meeting or the fertilised egg from reaching the uterus. Other disorders affect the release of eggs from the ovaries, and others affect males by reducing sperm number and activity. These challenges have driven the development of in vitro fertilisation (IVF), which offers a human-made bridge to pregnancy when the natural path is blocked. IVF is a process whereby the act of fertilisation, initial embryo division and implantation are conducted in the laboratory under the guidance of scientists.



IVF allows scientists to microscopically examine and genetically screen embryos for abnormalities before implantation

Sperm injection

Males with semen that contains millions of healthy and active sperm cells per millilitre are often able to achieve fertilisation organically. But semen harbouring a low sperm count, irregular-shaped sperm or sperm that aren't particularly mobile can find it difficult or even impossible. Sperm injection provides an alternative means to achieve fertilisation. Clinicians can use micropipettes to hold the egg in place and directly inject sperm cells into the egg using a micro-sized needle, allowing the sperm cell to reach its goal.

Tiny needles can be used to penetrate the egg and directly inject sperm

IVF allows scientists to microscopically examine and genetically screen embryos for abnormalities before implantation

The world's first 'test tube' baby

In 1977, Lesley Brown – who was struggling with infertility due to blocked fallopian tubes – was put in contact with scientists Dr Robert Edwards and Dr Patrick Steptoe. Steptoe was an expert in obtaining eggs from ovaries and Edwards an expert in fertilising human eggs in a petri dish. Together, the two offered Lesley Brown the opportunity – albeit one with a slim chance of success – to artificially fertilise her eggs with her husband's sperm. Without the use of hormones to manipulate her natural menstrual cycle and increase egg production, the scientists overcame the odds and successfully performed the first in vitro fertilisation and implantation of a single lab-fertilised embryo.

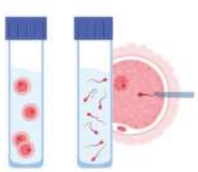
Fertilisation in a laboratory

The artificial fertilisation technique that helps parents overcome natural barriers to conception

1

Increasing egg supply

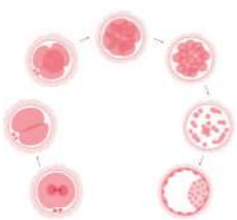
Hormones are administered which suppress the natural menstrual cycle. These are followed by fertility hormones that boost egg production by the ovaries.



2

Collection and fertilisation

Eggs are collected using a needle inserted into each ovary and fertilised with sperm by either mixing or directly injecting the sperm into the egg.



3

Embryo development

The embryo is stored in an incubator and begins to divide. Many clinics wait until the cell has divided into a blastocyst before implantation.

4

Genetic screening

DNA from a single or small number of cells is removed from the embryo and tested for abnormalities.

5

Cryopreservation

Healthy embryos that will not be implanted immediately can be frozen and stored safely for years for later implantation.

6

Embryo transfer

The embryo is implanted in the uterus using a flexible tube called a catheter, which is carefully guided into place using an ultrasound scan.

One baby, three parents

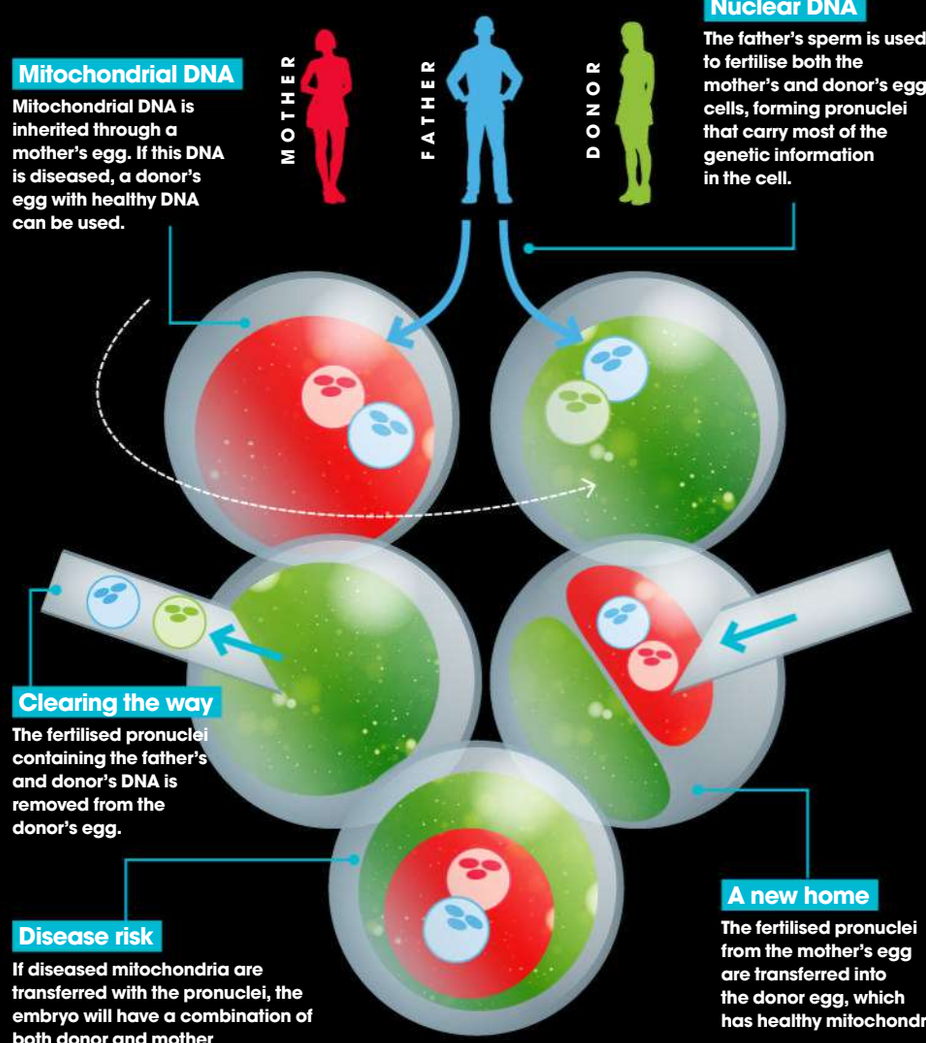
How doctors can use different genetic material

Nuclear DNA resides inside the nucleus of our cells. This DNA is huge, composed of reams of instructions 3.3 billion base pairs in length. Nuclear DNA comes from both our mother and father and is responsible for the vast majority of characteristics we display as we develop. However, our cells also host a small chunk of independent DNA that lives inside cellular components called mitochondria, which are energy-producing factories that power our cells. Mitochondrial DNA comes solely from our mother and is inherited from the fertilised egg cell at the beginning of gestation.

Mitochondrial DNA is miniscule in length compared to its nuclear counterpart, measuring around 16,500 base pairs in length, and contains instructions only for the function of mitochondria. In rare cases, a mother can harbour a catastrophic mutation in this DNA that prevents healthy embryos from developing. To circumvent this problem, scientists have developed a technique that combines nuclear DNA from two genetic parents with mitochondrial DNA from a donor. This removes the risk of inheriting mitochondrial diseases and means that the birthed baby will forever carry DNA from three people.

Room for one more

Replacing a mother's diseased mitochondrial DNA allows a baby to carry genes from three people



Three-parent babies have nuclear DNA from their mother and father and mitochondrial DNA from a donor

Physiologist Robert Edwards (left) and gynaecologist Patrick Steptoe (right) were the forerunners of successful IVF treatment

Embryos fertilised in the laboratory can be safely cryogenically preserved for over a decade

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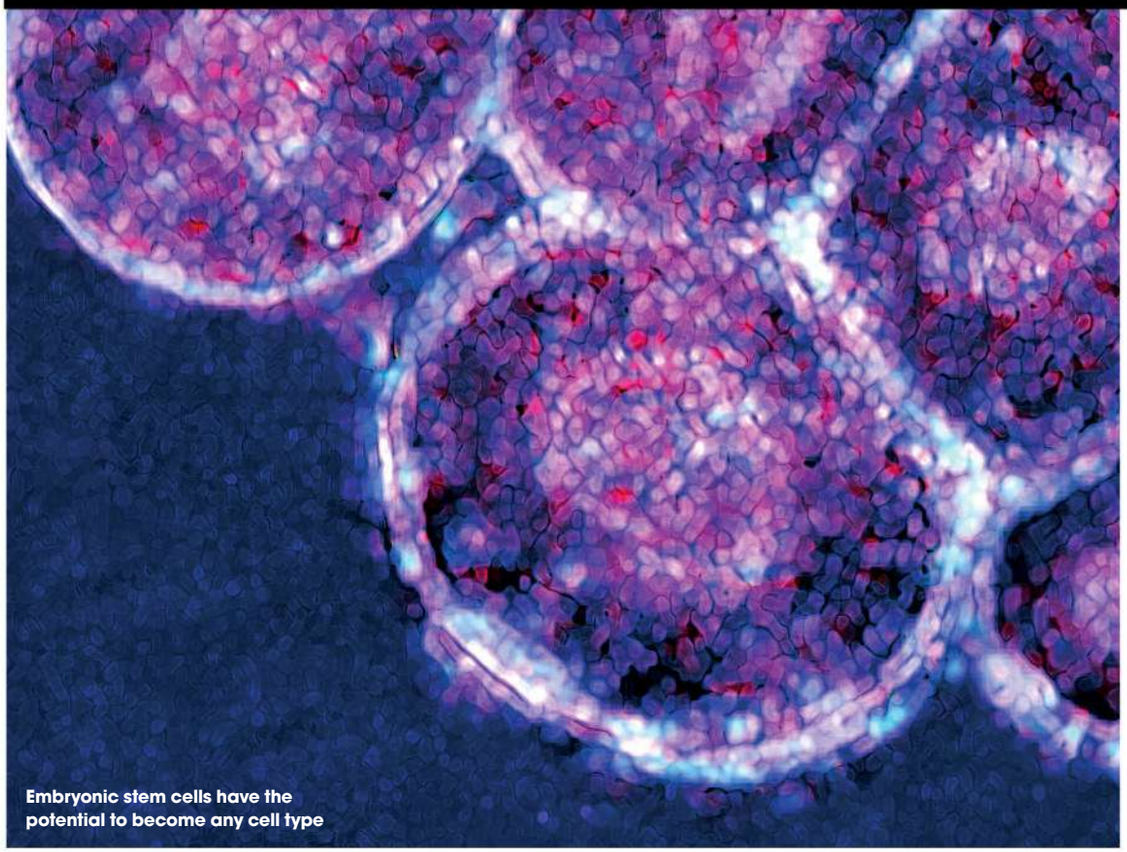


Embryonic stem cells have the potential to become any cell type

Cloning

The egg cell is essential, designed to ensure that the encoded DNA in the nucleus develops into an embryo. But scientists wondered if the egg could only drive the embryonic development of DNA from both parents or if it could transform any nuclear DNA into an embryo. In the 1960s, they started to find out. Beginning with frog cells, as they're large and easier to manipulate, scientists removed the nuclear DNA from a fertilised egg and replaced it with nuclear DNA from an intestinal cell of an adult frog. After around 40 days, the result was a tadpole genetically identical to the frog that had donated the intestinal cell, as all the nuclear DNA had come from one animal.

Dolly the sheep was the first mammal successfully cloned

The science of stem cells

A fertilised embryo that nestles into the uterine wall holds mammoth amounts of potential. The cells destined to become a foetus at that moment all look alike and number in the mere hundreds. Yet the organism that will arise from this small enclave will one day boast trillions of cells and be composed of a plethora of specialist cell types. How can the multitude of different cell types that make up our eyes, brain, lungs and skin come from such a small number of similar cells? The answer to this exponential increase in complexity and specialisation comes from stem cells.

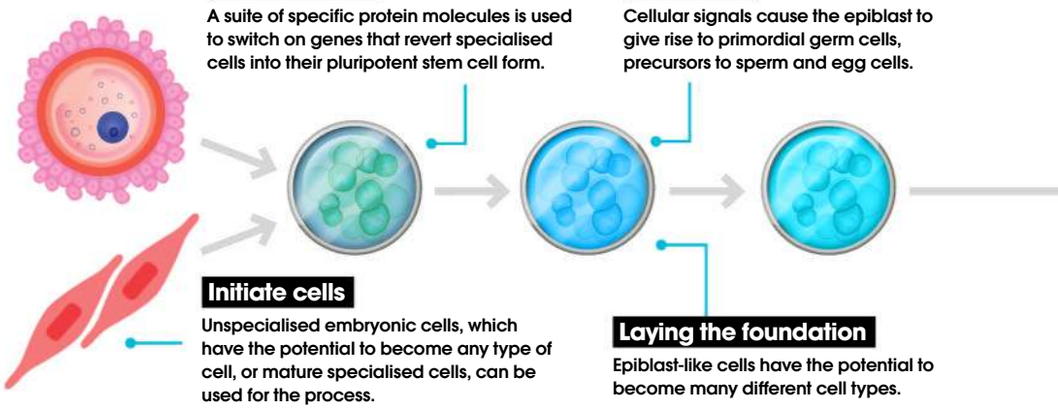
Every cell in the human body contains all the genetic information needed to perform any role. But for our bodies to develop and function efficiently, we need skin cells to behave like skin, and for muscles to behave like muscles. For this to happen, our cells become specialised, or differentiated, into particular cell types, meaning they only use a part of the genetic information available in their DNA.

However, all cell types begin their existence as stem cells, undifferentiated cells that have the potential to become many different cell types. Embryonic stem cells are there at the origin of our developmental journey. As the embryo grows and develops into a foetus, chemical signals received by the stem cells begin their journey of differentiation, sealing their fate to become certain cells by silencing and unlocking specific parts of their DNA.

The malleable power of stem cells also represents remarkable opportunities for those who can harness them. As well as being able to recover embryonic stem cells from early embryos, recent advances have discovered the cellular signals needed to convert differentiated cells back into their unspecialised states. This provides multiple means for scientists to transform cells into any type of their choosing. Research is underway to grow entire transplant organs for a patient from their own cells, and we can even utilise stem cells to generate egg and sperm cells that give rise to new life.

Engineering an egg factory

How an embryo or cell can be transformed into a fertilisable egg

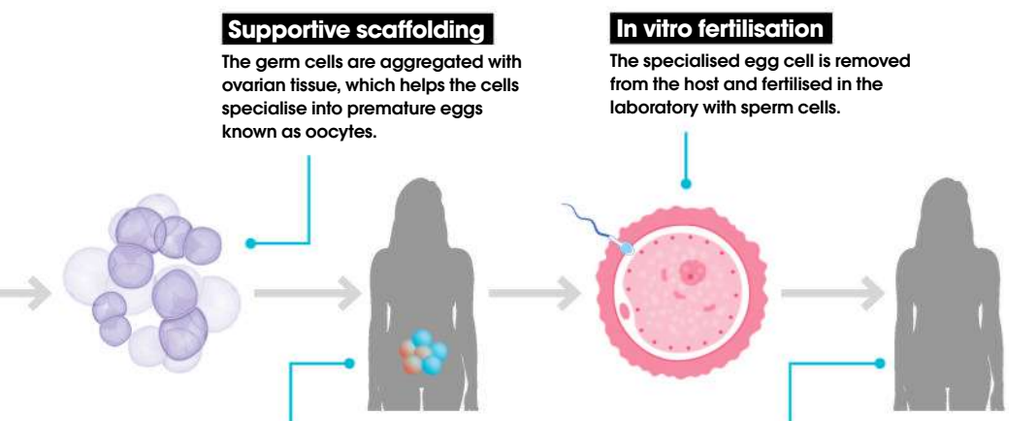


The advantages of cloning

World expert Professor Irina Polejaeva discusses cloning in the agricultural industry

"One key benefit of cloning is that it allows you to introduce specific traits over just one generation. A desired trait may be caused by a specific DNA change and only be naturally present in one breed of cattle and lacking in another. However, we can design clones so that they have attributes from both breeds. For example, horn growth in dairy cattle can be a danger to other animals and those that care for the animals. To induce a lack of horns through a genetic path, you'd usually need to go through multiple generations of breeding, but alternatively we can edit the gene in cells prior to cloning to get this trait immediately. This helps to improve animal welfare as we can avoid farming practices like the dehorning procedure, which is when a calf's horn buds are burned to prevent them from growing."

Polejaeva studies the production of transgenic cloned animals for use in agriculture and biomedicine



Embryo growth

What allows embryos to develop such complex structures? We speak with Dr Megan Davey to find out

Davey is a group leader at the Roslin Institute, where she researches chicken embryos to study limb development

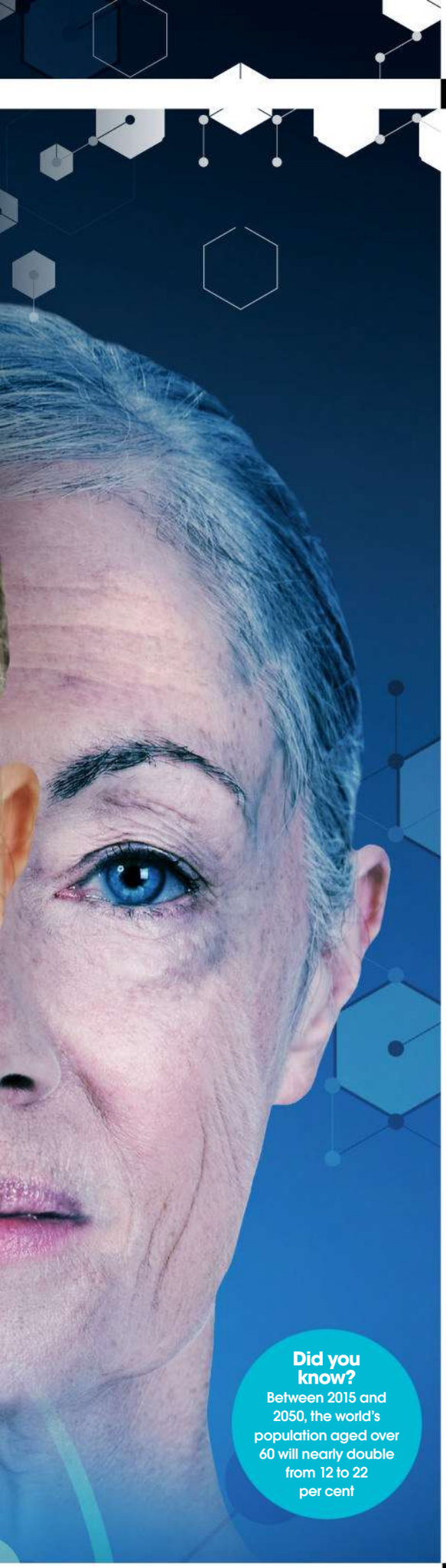
The development of an embryo is an amazingly complex phenomenon. Can you outline some of the major proteins involved in driving this process?
One of the main proteins responsible for limb patterns and growth is known as the Sonic hedgehog (SHH) protein. For SHH to work correctly, it has to come on for exactly the right amount of time and have exactly the right amount of activity. If you lose the activity of this protein, embryos develop with unusual differences. Too much can cause too many fingers to form; too little and things like cyclopia, where the eyes don't part and the nose doesn't develop properly, can occur. Another important protein is TALPID3, which affects the activity of centrosomes, cellular structures that are important for cell division. When the cell is not dividing, the centrosome migrates up to the cell surface and docks onto the cell membrane. Cells use centrosomes as their compass, but cells that lack the TALPID3 protein lose their spatial awareness. Centrosomes in these cells continue to migrate, but they don't migrate in the right direction. Instead, they move all over. This means that cells can end up growing the wrong way.

Could investigating stem cell activity lead to any medical applications?
We currently don't know how to regenerate fingers, and we don't know if there's a stem cell for regenerating fingers. My hypothesis is that embryos may have stem cells at the tips of their growing digits. We're currently investigating useful genetic tools in chickens, and one that we're developing is called the Brainbow chicken, which allows us to visually mark cells and see where they go during development. We can use this to label the cells found at the end of the digits and see if they behave like stem cells, allowing us to learn more about how to regenerate fingers.

Chicken embryos can be filmed under a microscope to track how embryos develop their limbs

© Getty / Alamy / Roslin Institute, University of Edinburgh / Irina Polejaeva / Megan Davey, Roslin Institute

HUMAN GENETICS



Can we live forever?

What is ageing and why do we get older? We look at the science of senescence and the technologies tackling the inevitable

Ageing is a fact of life we can't escape no matter how hard we try; though, as a species, we're getting better at prolonging the process. For the first time in human history, the global average life expectancy is above 70 years old. In comparison, back in 1950, the global average was 45 years old. We can predominantly thank the advancement of medicine for letting us live longer, but at what point do we stop growing and start ageing?

It's generally understood that once we surpass sexual maturity in our late 20s we make the transition from developing into ageing, also referred to as senescence, which means 'the process of growing old'. After sexual maturity, our bodies become less efficient at dealing with physical stress and maintaining biological systems. That seems to be because of the way our species has evolved.

It might make more sense that, like any machine, if you keep your body well-fuelled and maintained, you could live indefinitely. Generally speaking, many evolutionary biologists have concluded that we age simply because the driving force of evolution, natural selection, hasn't accounted for fitness and function at an older age.

Of course, humans aren't alone in this. The majority of other species have evolved a similar reproductive life cycle – but not all of them. Many cold-blooded species such as lizards retain their fitness and reproductive abilities and are considered to have negligible senescence. These animals age very slowly and typically die from non-age-related events such as predation, disease or natural disasters.

Did you know?
Between 2015 and 2050, the world's population aged over 60 will nearly double from 12 to 22 per cent

Cellular ageing

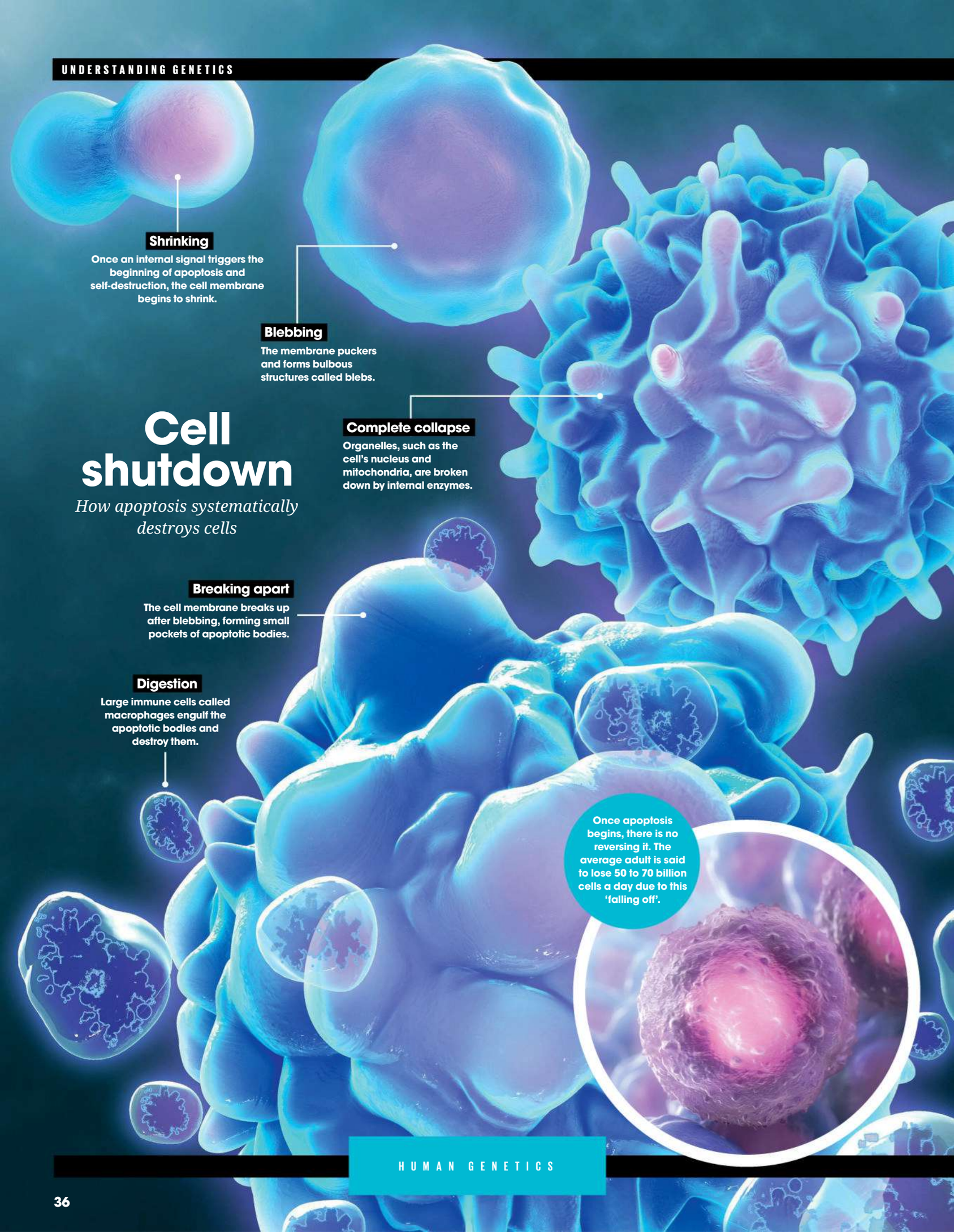
Although we recognise ageing in humans as wrinkled skin, joint pain and grey hair, senescence occurs on a much smaller scale. More than 37 trillion cells make up the human body, and each one will have its own life cycle that contributes to your body's overall ageing.

Each of your cells has a Hayflick limit, named after the scientist Leonard Hayflick, who discovered it. This limit is how many times a cell can divide before it can't divide anymore and dies. A normal human cell has a Hayflick limit of between 40 and 60 divisions. This is because with each division cells lose some genetic information. Long chains of DNA called chromosomes in the cells' nuclei lose non-coding sequences of DNA called telomeres from their tips. With each replication, these telomeres become shorter and shorter until the cell can no longer successfully divide.

Reaching their limitations, cells will undergo a form of self-destruction called apoptosis, from the Greek word for 'falling off', referring to leaves on a tree. This orderly process involves enzymes, called DNases, breaking down a cell's

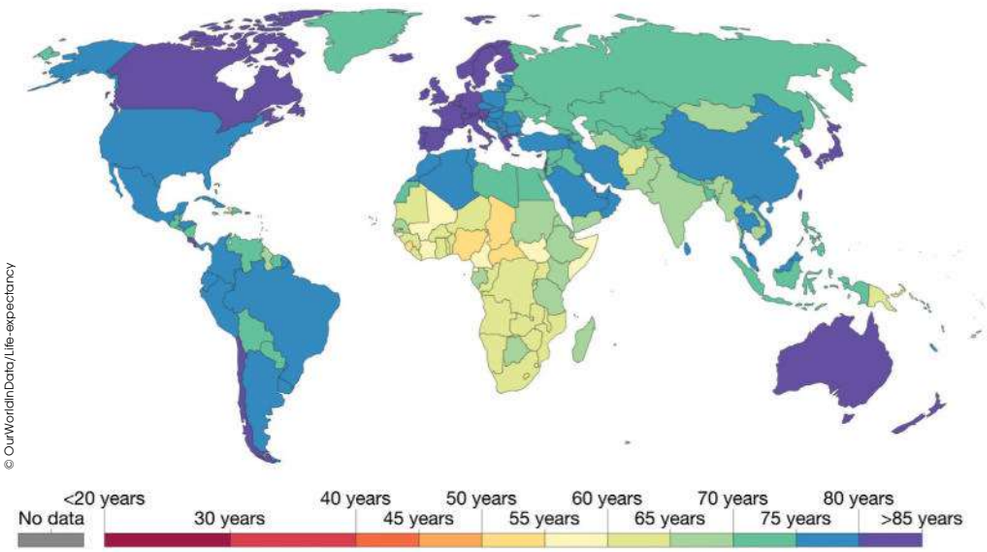
Cell shutdown

How apoptosis systematically destroys cells



Once apoptosis begins, there is no reversing it. The average adult is said to lose 50 to 70 billion cells a day due to this 'falling off'.

Life expectancy around the world



© OurWorldInData/Life-expectancy

genetic information. Immune system cells called macrophages eat up the cell's remains and remove it. This is different from necrosis, however, whereby a cell will die away after it is physically damaged.

This cellular life cycle is what keeps our bodies in check; without a Hayflick limit, cells would continue to divide, growing to form masses. Cancer cells have no Hayflick limit, which is why they grow rapidly and form tumours that can spread around the body.

However, it is believed that when a cell's DNA is damaged, the process of apoptosis is halted, and the cells become 'senescent'. Stuck in a phase between being alive and dead, these are often referred to as 'zombie cells'. They can no longer perform their allocated function, and they also stop reproducing. As a result, the cells build up and become a major contributor to the process of ageing.

As these zombie cells linger over time, they cause inflammation and other age-related diseases such as cancer and cardiovascular disease. They play a particular role in the degradation of neighbouring tissue and cells, which leads to the development of degenerative disorders related to age such as dementia.

The appearance of ageing

Greying hair is a universal symbol for ageing. It's commonly misunderstood that your hair 'turns' grey when it's just your hair follicles running out of pigment over time. This

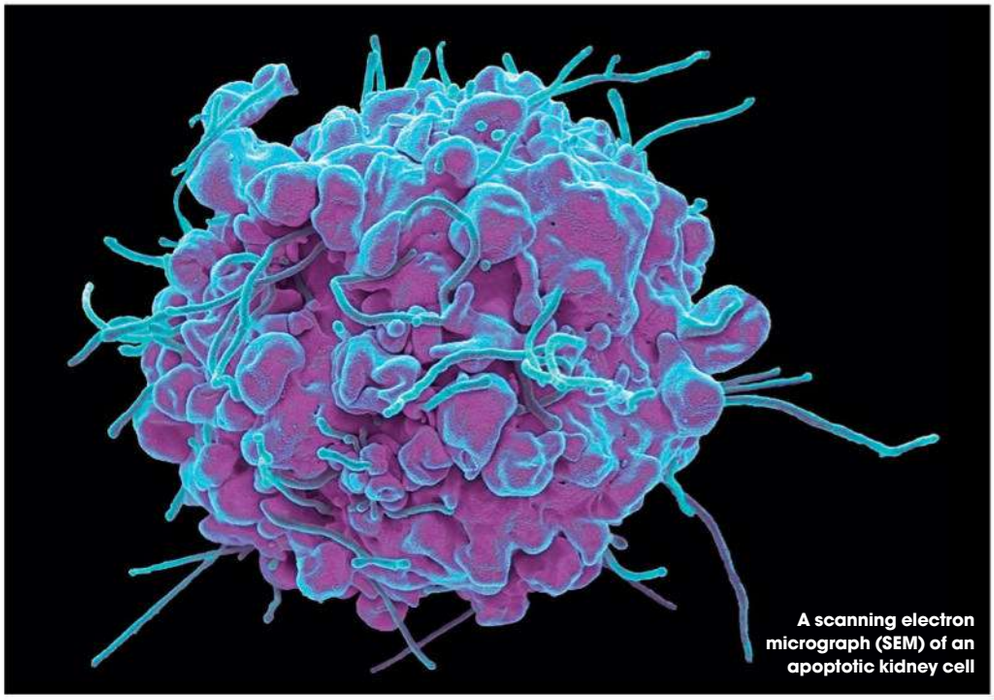
Jeanne Calment was verified to be 122 years old when she passed away, a feat yet to be surpassed.

Too old to age

Is it possible for a human body to reach a certain age and stop ageing? A study conducted in 2018 found that yes, it can happen, but you have to reach 105 years old first. Research conducted at the Sapienza University of Rome in 2018 found that, when looking at 3,836 Italians who were over the age of 105 between 2009 and 2015, the risk of death plateaued.

As we age, our risk of death naturally increases – for example, in your 50s, the risk of dying is three times higher than in your 30s. However, the study suggests that the probability of living between 106 and 107 years is the same as between 111 and 112 years. It remains unclear why this might be, with the need for more study into potential contributing factors, such as a person's genes.

If you reach your 100th birthday, you have a 60 per cent chance of celebrating your next one



A scanning electron micrograph (SEM) of an apoptotic kidney cell

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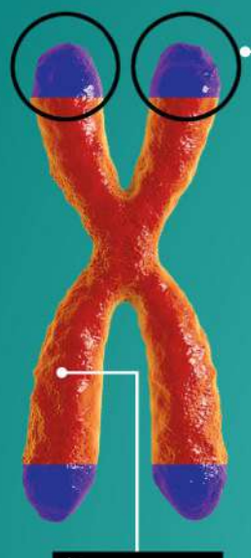
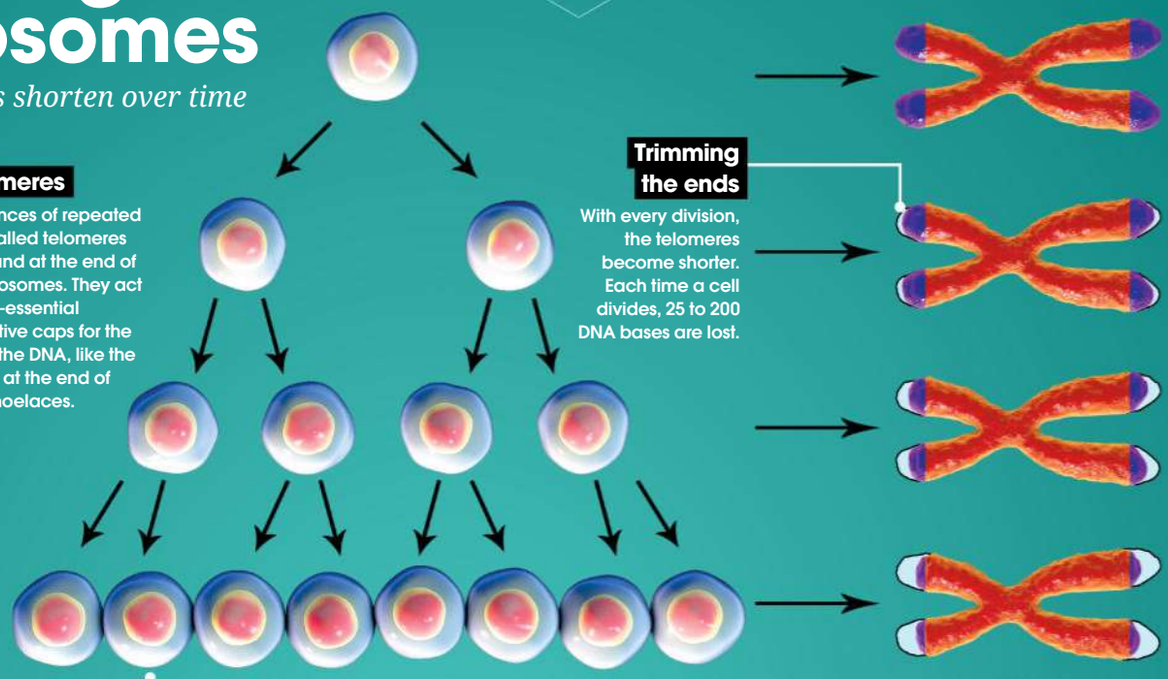
Cutting chromosomes

Here's how telomeres shorten over time



Telomeres
Sequences of repeated DNA called telomeres are found at the end of chromosomes. They act as non-essential protective caps for the rest of the DNA, like the plastic at the end of your shoelaces.

Chromosome
Each cell in our bodies contains 23 pairs of long DNA chains called chromosomes.



Trimming the ends
With every division, the telomeres become shorter. Each time a cell divides, 25 to 200 DNA bases are lost.

Cell division
Human cells can divide 40 to 60 times before reaching their Hayflick limit. However, stem cells have a few more, around 72 times.

Forming wrinkles

How skin folds to create laugh lines

Epidermis
Younger skin is packed with lots of moisture, keeping it smooth and plump.

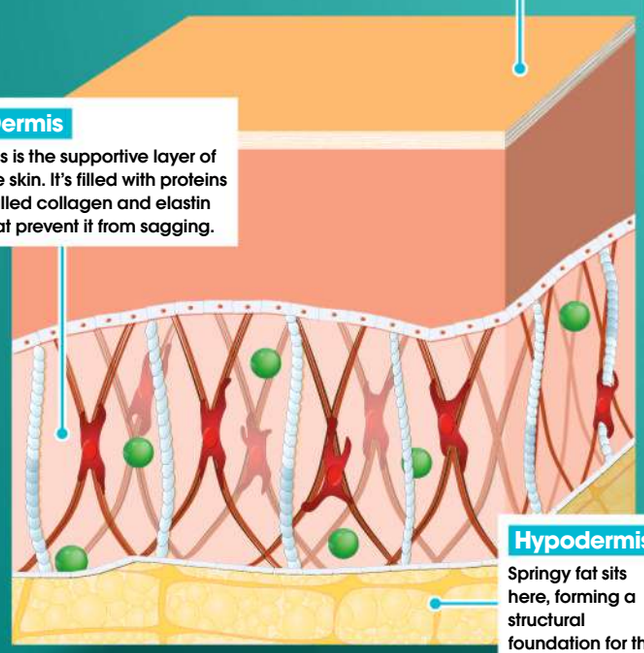
Dermis
This is the supportive layer of the skin. It's filled with proteins called collagen and elastin that prevent it from sagging.

Hypodermis
Springy fat sits here, forming a structural foundation for the layers above.

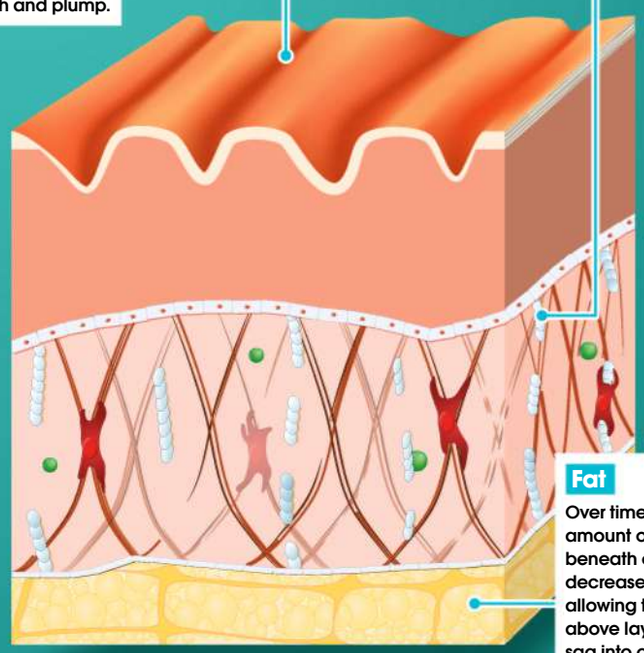
Moisture
Wrinkles begin to form when a lack of moisture causes skin to fold into the dermis layer.

Collagen
Levels of collagen and elastin are diminished over time, which act like support beams for the epidermis.

Fat
Over time, the amount of fat beneath our skin decreases further, allowing the above layers to sag into one another.

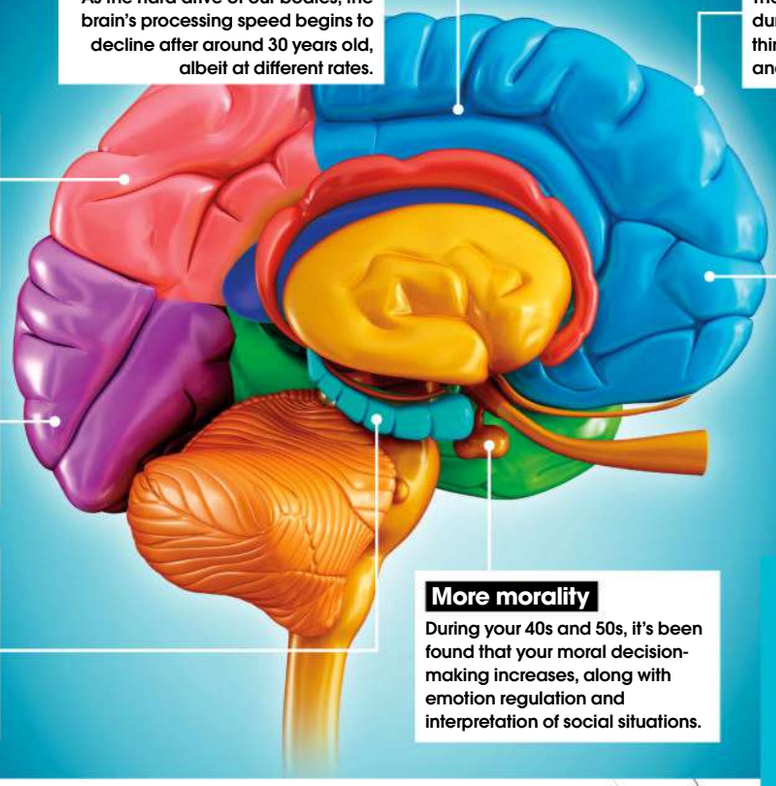


Younger skin



Older skin

Seven ways your brain changes as you age



Processing speed
As the hard drive of our bodies, the brain's processing speed begins to decline after around 30 years old, albeit at different rates.

Getting thinner
The cerebral cortex begins to thin during middle age. This cortical thinning leads to reduced memory and cognitive function.

Shrinkage
At around 30 years old, your brain begins to shrink, albeit at different rates and in different regions. The decrease in size ramps up a little by the time you reach 60 years of age.

Attention span
From as early as your 20s, your ability to manage multiple tasks like reading a recipe while listening to music, or filter out distractions like following what your friends are saying in a busy restaurant, can become more difficult.

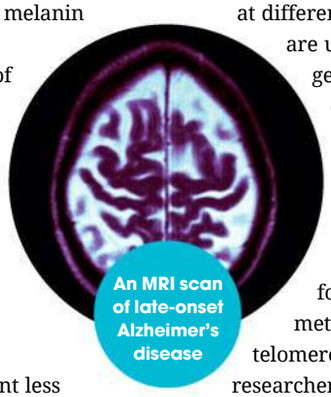
Chemical communication
Neurotransmitters such as dopamine, acetylcholine and serotonin decrease as we age. These enable the communication between nerve cells, which give us our cognitive function.

Memory
We often associate ageing with losing our memories, and part of that is because areas of the brain associated with forming memories, such as the hippocampus, shrink over time from your mid-30s.

More morality
During your 40s and 50s, it's been found that your moral decision-making increases, along with emotion regulation and interpretation of social situations.

biological hair dye is called melanin, and it's also the pigment that gives your skin its colour. As we age, the production of melanin at the follicles declines, and grey hair begins to emerge, typically from your 30s. Around 50 per cent of the population will be at least partially grey by the time they are 50. But melanin decline isn't exclusive to hair follicles as we age. Our number of melanin-containing skin cells, called melanocytes, decreases by 8 to 20 per cent per decade after the age of 30.

Along with the loss of melanin, our skin also loses components that keep it firm and smooth, such as collagen and elastin. After the age of 20, a person makes around one per cent less collagen in their skin every year. This leads to the formation of wrinkles and generally less plump skin. What does appear to continue to grow, however, are our ears and noses. Researchers at the University of Milan calculated that the total surface area of the nose of people aged 65 to 80 is typically 15 per cent larger than a nose on the face of an 18 to 30-year-old. This is because as we age, the cartilage that has built those features goes through a process that makes it thicker but less elastic.



An MRI scan of late-onset Alzheimer's disease

The process of ageing doesn't affect us all equally. Many of us go grey or lose our hair sooner than others, and wrinkles will appear at different stages of our lives. Our bodies are unique and are affected by our genetic blueprints and the impact our environment has on us, meaning that everyone ages at different rates. A study from Duke University explored this on a cellular level. Researchers monitored different markers for risks of age-related disease, metabolism and the length of telomeres of 1,000 participants. The researchers checked in on them at 26, 32 and 38 years old, and found that, in general, participants' biological age correlated with how many birthdays they had celebrated. However, there were some extreme exceptions. One participant had a biological age of 28 – essentially not ageing since the trial began – while another had biologically aged to around 61. That suggests that they aged three years for every birthday on average.

5 Ways to keep your mind sharp

1 Exercise
Studies in animals have found that regular exercise increases the number of blood vessels that feed oxygen to your brain. It's also been found that new nerve cells and the connections between them are increased, which improves your cognitive abilities.

2 Sleep
Getting seven to eight hours of sleep a night has been found to consolidate memories more efficiently. Some studies have found that bad sleep increases proteins in the brain that contribute to impaired brain function.

3 Eat well
Having a healthy diet will improve many aspects of your life, but studies have shown that those eating a Mediterranean-style diet filled with vegetables, nuts, fish and fruit are less likely to develop conditions such as Alzheimer's.

4 Stay social
Social interactions have never been more important to our mental health, but regarding ageing, safe social interactions help prevent the effects of depression and stress, which contribute to memory loss.

5 Train your brain
Completing puzzles such as jigsaws, sudoku or crossword puzzles stimulates new connections between brain cells and develops your brain's ability to problem-solve and adapt to new situations.

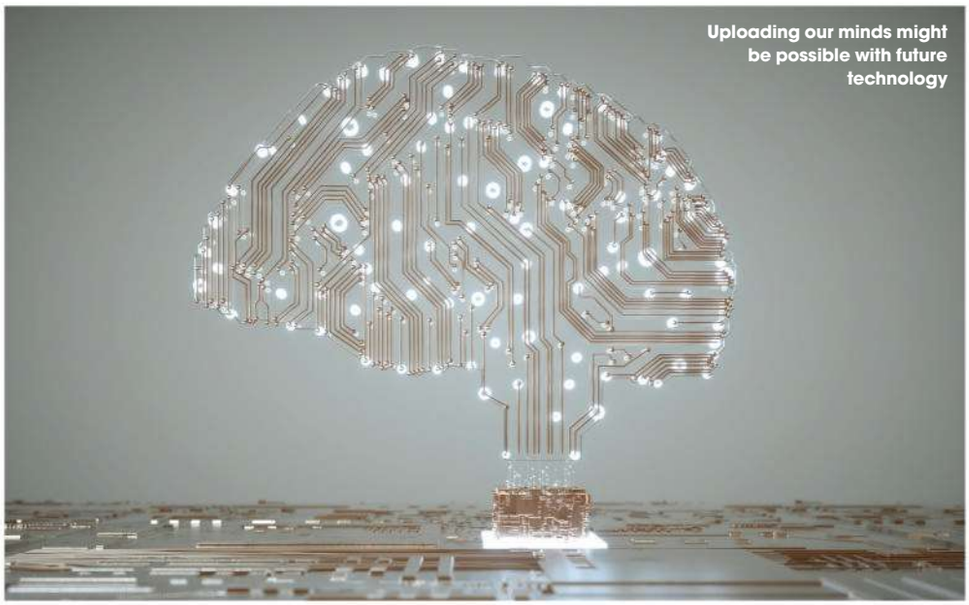
© Getty

Who wants to live forever?

The science that seeks to slow down the process of ageing

Upload yourself

There may come a point when attempts to prevent ageing turn from the biological to the digital. If you truly want to live forever, then uploading your brain may be a real option in the future. When, however, remains unclear. The science is called Whole Brain Emulation (WBE), and in theory, it would involve uploading your consciousness into a computer, including all of your thoughts and feelings. However, the first and biggest hurdle scientists face is mapping the human brain. There are roughly 86 billion neurons in your head and each neuron can connect to 10,000 other neurons. Thus far, scientists have only been able to map the 302-neuron brain of a nematode, so we're a long way off navigating the human mind. Nevertheless, many tech companies and research institutes are working to map the whole brain in the hopes of one day recreating it online.



Uploading our minds might be possible with future technology

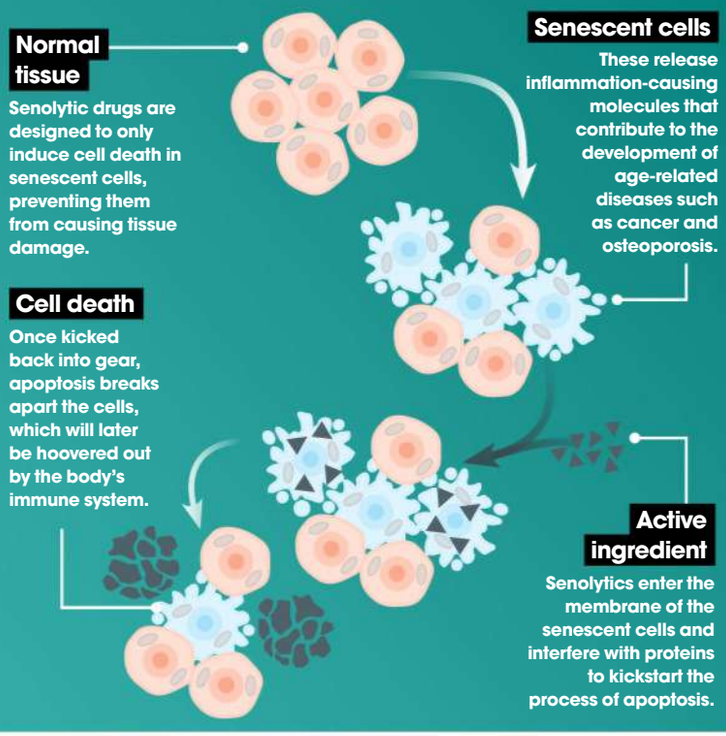
Anti-ageing pills

Could stopping the process of ageing be as simple as popping a pill? Researchers at the Mayo Clinic in Minnesota have been developing so-called senolytic drugs. These pills work by inducing apoptosis in senescent cells, preventing them from gathering. This prevents them from damaging neighbouring cells and causing age-related illnesses. So far, this type of time-halting medicine has only been successfully trialled with animal subjects, though human trials are underway.

Senolytic drugs are not yet available, but could one day revolutionise the way we age

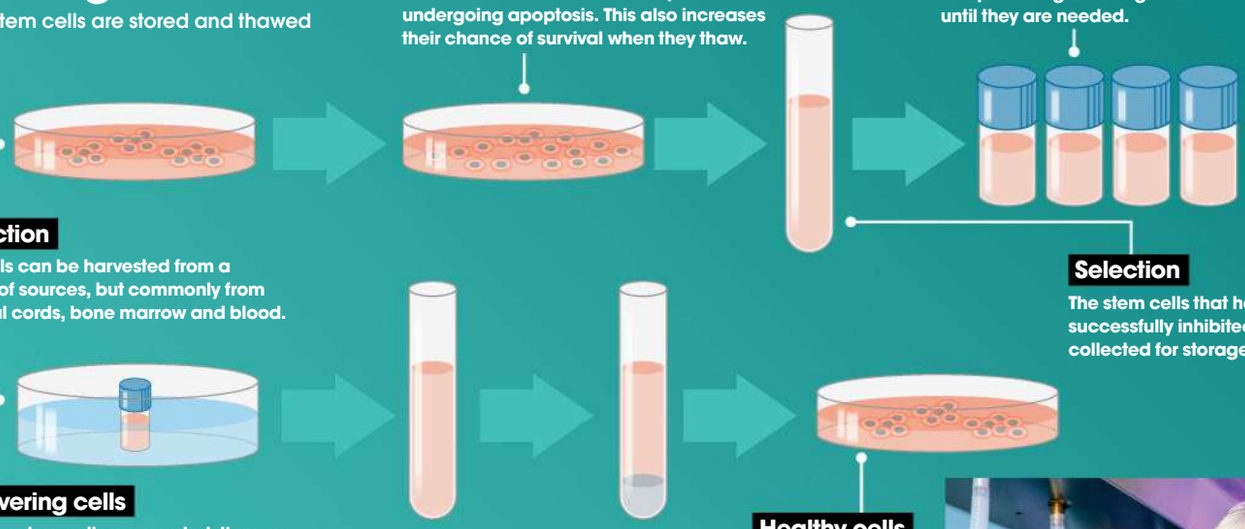
Inducing self-destruction

How senolytic drugs could keep us young



Freezing the future

How stem cells are stored and thawed



Stem cell security

One way people are clinging to the hope of eternal youth is by cryogenically freezing their stem cells. Stem cells are special cells that can transform into any other type of cell in your body. By storing these cells, the hope is that one day they can be used for treatments to battle any future illnesses.

Currently, the only stem cells used to treat conditions are those that change into blood cells for transplants in blood cancer patients. These cells can be harvested from sources such as the umbilical cord at birth, adult bone marrow or fat tissue. The cells are then frozen and stored for future use.

Pure oxygen and a pressurised chamber could be the key to unlocking a long life

Young blood myth

People have gone to extreme lengths to preserve their youth, both cosmetically and biologically. However, in February 2019, the US Food and Drug Administration cautioned the public about receiving blood transfusions from young people in attempts to turn back the biological clock, saying that this had "no proven clinical benefit". Transfusions were being offered by companies such as California start-up Ambrosia, with a price tag of $8,000 (around £5,780) per litre of blood plasma – the liquid component of blood – from people aged between 16 and 25 years old. Claims that the protein-filled plasma could help with ageing-related ailments and diseases, such as inflammation and Alzheimer's, have not been substantiated by a great deal of scientific research, with limited studies investigating if the vampiric therapy provides any health benefits.

Could transfusing the blood of young people keep you youthful? Probably not

Breathing young

A recent study conducted at Tel Aviv University has revealed that hyperbaric oxygen treatments could halt the ageing process. Over a research period of 90 days, 35 participants over the age of 64 were given hyperbaric treatments, which involved inhaling pure oxygen in pressurised environments for 90 minutes a day, five times a week.

Blood tests showed that the bodies of the participants changed on a cellular level to what they would have been like 25 years earlier. Researchers found that telomeres lengthened by 38 per cent and a 37 per cent decrease in the presence of senescent cells. More research is needed to fully understand how hyperbaric treatments may intervene in the process of ageing, but it's a promising start.

© Getty

Immortality

Is the future of everlasting life cryonics?

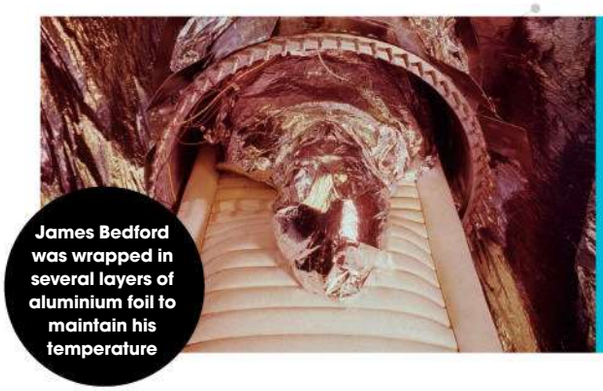
One way in which you could give yourself the opportunity to live even after death is with cryonic suspension. It may have been able to bring back Austin Powers after 30 years of suspension, but beyond the world of science fiction, the practicalities of cryonics remain a mystery. Right now we have the technology to cryogenically preserve a human body, but remain clueless on how to revive them when the time is right. It's the belief that humankind will one day find a way to successfully thaw patients and treat whatever illnesses led to their death. The world leader in cryonics, Alcor, currently has 181 patients and has been storing humans for 49 years, including the company's founder, Fred Chamberlain.

The process of preserving a human body through cryonics involves replacing the water content of a body with a chemical cryoprotectant, which works like antifreeze. This is to prevent ice crystals from forming during freezing and irreversibly damaging the body. Once filled with cryoprotectants, the body will eventually be placed into a tank of liquid nitrogen at around -196 degrees Celsius, where it will be stored.

The biggest challenge of cryonics is to find out how it can bring people back to life. Science has successfully frozen simple cells such as eggs and sperm in suspension and thawed them with their functions intact. It remains unclear as to how scientists will bring back an entire human body. So far, the only success scientists have had has been in bringing functionality back to the cryogenically frozen brain of a small rabbit.

We've got the science to safely cryopreserve the dead, but we're still unsure how to revive them

© Alamy



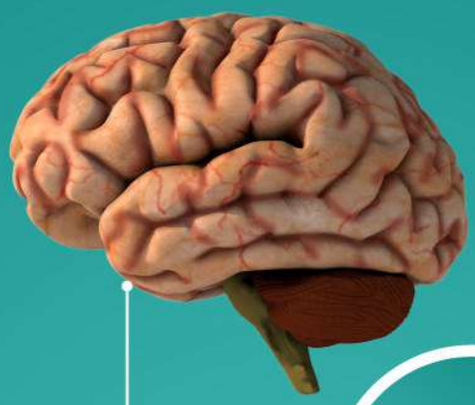
James Bedford was wrapped in several layers of aluminium foil to maintain his temperature

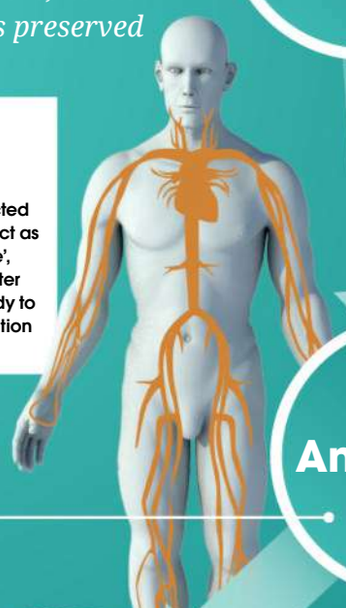
First cryogenic human

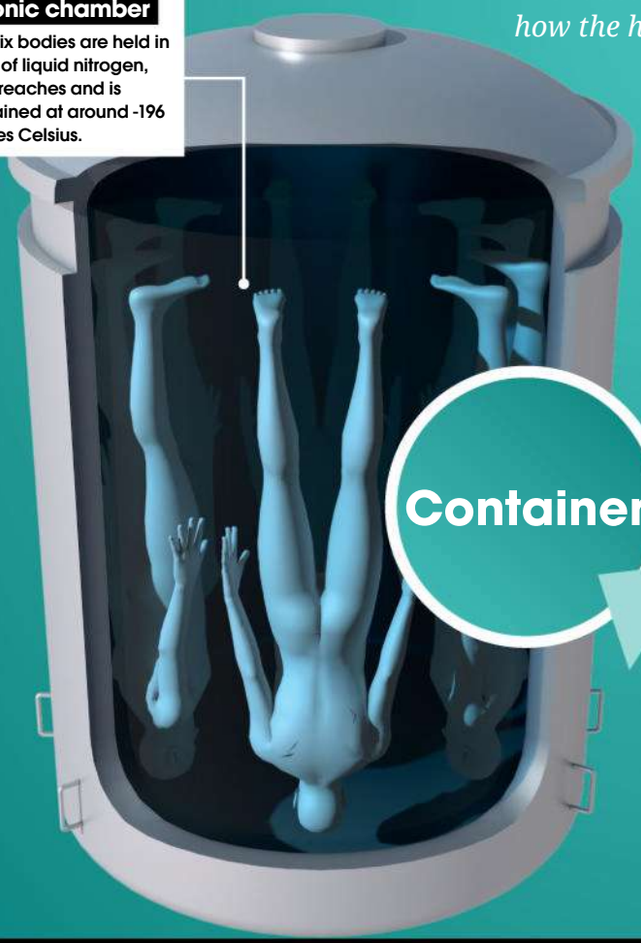
The first person to ever be cryogenically frozen was Dr James Bedford, a 73-year-old psychologist who died of cancer. In 1967, Bedford entered a cryogenic storage dewar, a special vacuum flask to store super-cold cryogens such as liquid nitrogen. Upon his death, Bedford's blood circulation was artificially maintained while he was being cooled. His body was injected with dimethyl sulphoxide, which can preserve tissue, before being moved to a liquid-nitrogen environment. It's since been found that this preservation method will most certainly have damaged the cells in Bedford's brain beyond any possible repair. Nevertheless, his body remains on ice at the Alcor Life Extension Foundation to this day.

Inside the cryo coffin

From death to deep freeze, here's how the human body is preserved







Death

Cooling

Heparin

Anti-freeze

Freezing

Container

Preparation
The body is packed with ice and injected with a blood-thinning drug called heparin to prevent the blood from clotting before being transported to a cryogenic facility.

Artificial breathing
Within minutes of death, the body has to be put onto a mechanical heart-lung ventilator to keep the brain supplied with oxygen.

Human antifreeze
A cocktail of chemicals is injected into the body to act as 'human antifreeze', replacing any water content in the body to prevent the formation of ice crystals.

Chill out
The body is then placed on dry ice and cooled until it reaches around -130 degrees Celsius.

Cryonic chamber
Up to six bodies are held in a tank of liquid nitrogen, which reaches and is maintained at around -196 degrees Celsius.

© Illustration by: Adrian Mann

How Genealogy Tests Work

Welcome to the world of the gene-ius DNA detectives solving the world's ancestral mysteries

HUMAN GENETICS

If, like many people, you're curious about where you come from, you'll no doubt have been tempted to take a genealogy test at some point. These clever bits of technology can help you discover your ancestral roots and maybe even connect you with one or two long-lost relatives. By analysing your DNA, these tests provide fascinating insights into your ethnic background and can reveal the countries, areas and regions that your ancestors lived in going back hundreds – or even thousands – of years.

Beyond uncovering your heritage with a genealogy test, you may even be able to learn about some inherited health traits you may have. It really is a fascinating way to explore your and your immediate family's personal history and understand the journey that your ancestors went on. And all from a simple sample you provide in mere seconds.

How they work

Have you ever sat back and pondered where your ancestors originated or if you have a distant second cousin you don't know about? Many folks have. The answers to such questions can often be provided to them by genealogy. It all starts with a little bit of spit. Here's how it works.

You send a saliva sample to a genealogy company of your choosing and they extract your DNA from it. The long and incredibly complex code that makes up your DNA is, of course, unique to you, but shares many similarities with your family and ancestors. Those similarities and links are how your connections and heritage can be plotted.

The company's scientists look at specific places in your DNA known as 'single nucleotide polymorphisms', or SNPs for short. They're like tiny little markers that indicate whereabouts - pretty much exactly - your ancestors came from. By comparing your SNPs with an enormous database of other people's DNA, they can find matches and estimate the makeup of your ethnic background. This comparison work is achieved using complex algorithms that can analyse thousands of genetic markers in the blink of an eye.

The technology doesn't stop there, though. Sequencing machines, which are at the beating heart of this process, then read your DNA and generate stupendous amounts of data off the back of it. This data is then processed to identify genetic variations that are shared among people from different regions of the world. By identifying these variations, the tests can pinpoint your ancestral origins with

"Company scientists look at specific places in your DNA known as 'single nucleotide polymorphisms'"

How genealogy websites caught a serial killer

It looked as if The Golden State Killer would forever elude the FBI

Joseph James DeAngelo, aka The Golden State Killer, was responsible for at least 13 murders, 51 sexual assaults and over 120 burglaries across the state of California between 1974 and 1986. Authorities were beginning to lose hope of identifying and catching him when he was, eventually, caught through innovative forensic techniques. Namely, the cross-referencing of his and his victims' DNA profiles with the records of genealogy websites.

American firms such as GEDmatch proved particularly useful. The technique identified distant relatives, enabling investigators to construct a detailed family tree of their suspect and his unidentified victims. They were soon able to pinpoint DeAngelo as their man. DNA samples were collected from discarded items belonging to the former police officer, which matched the crime scene DNA.

Arrested in April 2018, DeAngelo's case marked a milestone in using genealogy for solving cold cases, demonstrating the power of combining modern DNA analysis with genealogical research and databases to crack long-unsolved crimes. Here's hoping it brings many more criminals to justice in the future.

Without breakthroughs in genealogy, DeAngelo would likely have never been identified.

© Getty

incredible accuracy and even trace them back literally thousands of years.

Genealogy tests can also connect you with relatives you didn't even know you had. It does this by identifying segments of DNA that you share with others. It is like piecing together a huge family tree jigsaw puzzle.

So, with a bit of saliva and a lot of science, you can unlock the fascinating story of your origins in no time...

What information tests provide

These tests offer a potentially fascinating window into your ancestral past, revealing a wealth of information about your background and roots. One of the key insights they provide is your ethnic breakdown, showing the various regions of the world where your ancestors came from. You could discover that your heritage includes a complex mix of European, Asian, African, or other ancestries, painting an unexpectedly diverse picture of your family's journey through history.

In addition to your ethnic origins, these tests can occasionally match your DNA with living relatives you were completely aware of, and put you in touch with them – providing that they, too, have signed up to the same service. This can be an exciting way to potentially expand your family tree, learn about your relatives' stories and histories, and connect with your extended family.

Genealogy tests can also offer clues about your ancestors' migration patterns, revealing how they moved from one region to another over the centuries. Some tests can link your DNA back to ancient groups such as the Vikings, Celts or other indigenous peoples from all across the planet.

Your saliva provides enough biological detail from which scientists can extract your genetic blueprint

There's also a more practical side to it all. These tests can highlight genetic traits that you've inherited, things such as physical characteristics or even certain health predispositions. This can help you understand more about yourself, your health and your family's genetic legacy.

The potential drawbacks

In explaining how these things work and what they can do, we've already discussed why someone might want to take a genealogy test. But are there any potential *downsides*? Well, perhaps...

While genealogy tests can reveal fascinating insights about you and your origins, there might be disadvantages. Firstly, the results might not always be completely 100% accurate. Plus they can also sometimes be quite surprising or even a bit disappointing, depending on what you and your family were expecting to hear. Privacy can be another concern. Sharing your DNA data with companies always carries with it a possibility for misuse, something which could impact your and your family's data privacy.

23&Me CEO and co-founder Anne Wojcicki speaking at TechCrunch

Genealogy test providers: the big three

The major players in the family history tracing game

23andMe

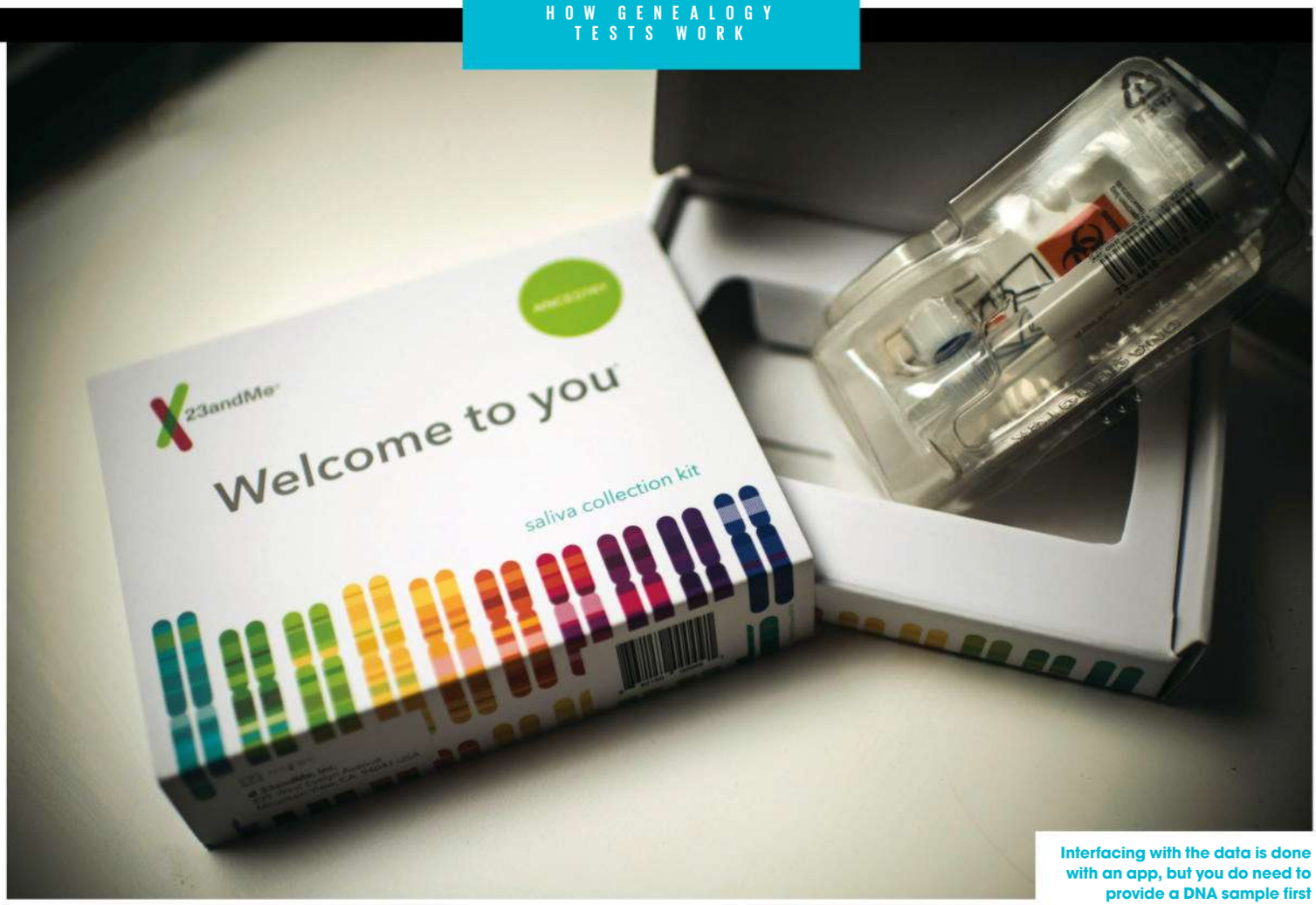
This San Francisco-based personal genetics company offers DNA testing for both ancestry and health insights. Founded back in 2006 by Anne Wojcicki, it provides detailed reports via a user-friendly platform. 23andMe was the first firm to offer autosomal DNA testing, something that all of the other testers now use.

Ancestry

Perhaps the best-known testing company on the market, Ancestry is the largest provider of consumer DNA testing worldwide, with more than 25 million users. Now available in some 128 countries, that platform has been around since 1983 and has a revenue of $1bn+ a year.

Living DNA

Relative newcomers Living DNA (founded in Somerset, UK, in 2016) offers DNA-based genealogy testing for both ancestral intrigue and insights into health, emphasising both accuracy and privacy. It also boasts insights into familial heritage that can go back up to an impressive 200,000 years.



Interfacing with the data is done with an app, but you do need to provide a DNA sample first

Then there's the potential fallout from discovering unexpected relatives or hidden family secrets. These can be emotionally devastating and cause serious stresses and strains within a family. On a slightly smaller scale, there is also the issue of cost. While many tests are costed fairly (around the £80/$80 mark for the base packages), others can be quite pricey, with additional fees applicable for more detailed information.

Finally, while genealogy tests can provide you and your family with some interesting information and details, they might not offer hugely significant practical benefits beyond just satisfying everyone's mild curiosity. The information is often interesting, but that's largely just it. It very likely won't reveal any grand revelation that will change a lot.

Whether you're looking to trace your lineage and build a family tree or satisfy your curiosity as to where you're from, genealogy tests really do offer a unique glimpse into your personal history.

"These tests can highlight traits you've inherited, such as physical characteristics or even health predispositions"

A quick step-by-step guide of what to expect

1 Order the kit
Buy your testing kit from a reputable genealogy testing company.

2 Collect saliva sample
Follow the instructions carefully and deposit a small sample of saliva in the receptacle provided.

3 Send your sample off
Secure the package and send it to the address provided by the testing company.

4 The lab analyses your DNA
Sit back patiently and wait while the laboratory processes and analyses your sample.

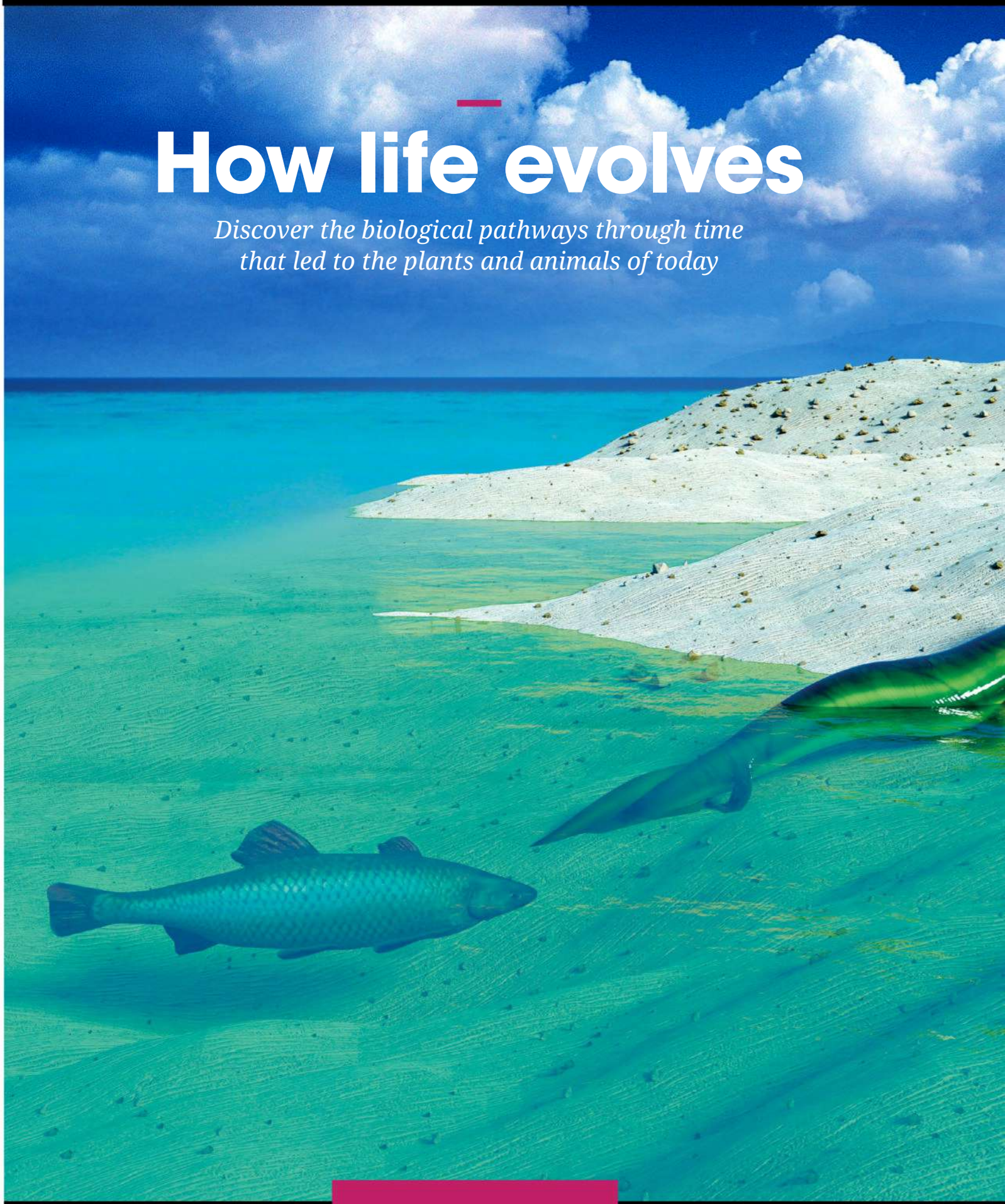
5 Receive and explore the results
Tear open the results and find out your genetic heritage!

© Getty

Evolution

How life evolves

Discover the biological pathways through time that led to the plants and animals of today



EVOLUTION

For around 3.7 billion years, life has followed a roadmap of evolution. The journey to modern-day life and the more than 2.16 million known species that reside on Earth has been guided by several different evolutionary pathways. The naturalist known as 'the father of evolution', Charles Darwin, first proposed the theory of evolution by natural selection after he jumped aboard the HMS Beagle in 1831 and sailed around the world for five years. On his travels, he discovered diverse wildlife, observing that they had anatomy specially adapted to their environments. He concluded that a species' survival depends on traits that suit its environment. This survival-of-the-fittest approach means that only animals with beneficial characteristics can continue to reproduce and pass them on to their offspring. Darwin proposed that through forces of evolution, an ancestral family tree formed below modern-day species, leading to a common ancestor at its roots.

Did you know?
The first reptiles evolved around 315 million years ago

Forces of evolution are varied and specific to an ecology niche. For many, evolution is driven by sexual selection, whereby qualities in potential mates – such as plumage vibrancy or big antlers – are chosen by a partner to successfully reproduce. For others, natural selection occurs when an aspect of a species' environment is altered, such as by climatic change, and they are forced to adapt or die. Those that can change go on to reproduce, leading to some anatomical and behavioural differences over millennia, creating new species along the way. Today, scientists refer to the creation of a new species as divergent evolution, where a new species separates from a common ancestor. Building on the work of Darwin, the term 'divergent evolution' was first introduced by evolutionist John Thomas Gulick in 1890. As the name suggests, divergent evolution occurs when a subgroup within a species diverges anatomically from the rest of the species, with these genes spreading until a new distinct species emerges. All life on Earth has undergone divergent evolution from a distant common ancestor, branching off into new families that form the tree of life.

For example, humans share more than 97 per cent of their DNA with the other great ape species on Earth: orangutans, gorillas and chimpanzees. Evolving from a common

© Getty

ancestor more than 25 million years ago, the great apes have diverged from their common lineage to produce an unknown number of now-extinct species that have paved the way for modern-day animals. Although they share a common ancestor, each ape has evolved distinctly different characteristics that have benefited them in their environment but have ultimately led to the development of each individual ape species.

Divergent evolution occurs over long periods, with some studies suggesting that it generally takes around 2 million years for a new species to emerge. However, not all animals are willing to wait that long, instead rapidly evolving several new species through a process known as adaptive radiation. One of Darwin's most notable observations involved a group of finches that lived throughout the Galápagos Islands. Across the different islands, Darwin observed that among the related finches, beak size and shape varied depending on what food they ate. He concluded that with each new generation, those who were better equipped to find food were able to survive – a concept that formed the basis for his famous theory on natural selection.

Similarly, in Hawaii, a group of birds called honeycreepers have undergone adaptive evolution to produce a diverse family of birds with beaks specialised for their food. Some boast big, long beaks to probe underneath bark to find insects, while others developed stout robust beaks for cracking seeds and picking berries. Upon reaching Hawaii around 3 million years ago, the common ancestor of the honeycreeper species wasted no time adapting to the array of food sources found across the archipelago. Within 2 million years, 50 species of honeycreeper emerged. But only 17 of them remain today.

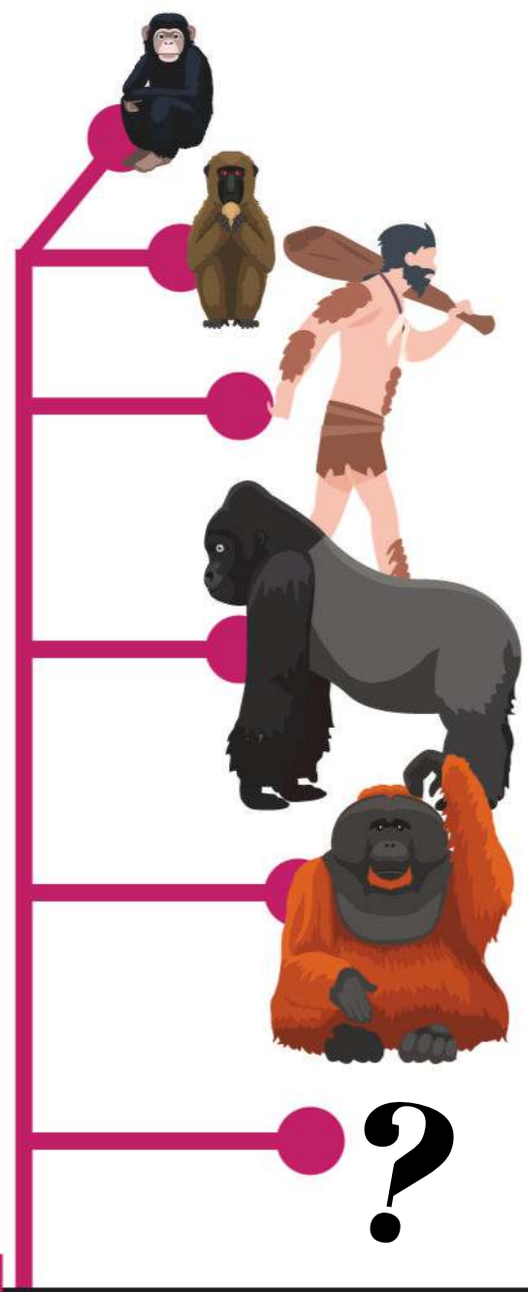
Where divergent evolution leads to the creation of entirely new species from a common ancestor, another evolutionary pathway, known as convergent evolution, produces new species that have evolved surprisingly similar traits. At first glance, you might forgive early biologists for mistaking dolphins for fish, or bats for a member of the bird family. That's because they share similar characteristics: dolphins evolved fish-like fins to swim, and bats developed bird-like wings for flight. However, dolphins and fish do not share a common ancestor, and neither do birds and bats. The two have separate evolutionary lineages, yet both

Birds and bats both evolved separately, resulting in wings despite having different lineages

Honey badgers evolved thick skin to evade the sting of a bee, but bees co-evolved a signalling system to attack badgers en masse

Human family tree

The road to becoming one of the great apes of the world



1.8 million years ago

The formation of the Congo River formed a barrier, splitting chimpanzees into two groups, one of which evolved into the modern-day bonobo.

6 million years ago

The evolutionary path of humans diverged from a primate ancestor shared with one of our closest living relatives today, the chimpanzee.

6 to 8 million years ago

Gorillas diverged from hominids. As more species of apes became extinct over time, gorillas evolved to become the largest of the great apes.

12 to 16 million years ago

Orangutans diverged from other apes of the Hominidae family in Asia, while the ancestors of the other great apes stayed in Africa.

Common ancestor

Though an exact common ancestor is unknown, a primate in the family Hominidae is responsible for starting the journey of ape evolution.

developed similar anatomical features, known as analogies. When two species occupy the same ecological niche and are therefore subject to the same evolutionary pressures, both evolve and adapt in similar ways, over time changing into new species that bear a resemblance to one another. For birds, the ability to fly emerged around 160 million years ago when a long-feathered dinosaur called Archaeopteryx, flapped its long feathers – which covered the skin of dinosaurs for millions of years. The elongated length of this dinosaur's arms helped generate some lift beneath them, allowing it to fly for short periods of time, in a similar way to a modern-day pheasant. Flight gave Archaeopteryx an advantage over other animals when evading predators, and also hunting prey from treetops. Bats, on the other hand, evolved only 50 million years ago, descending from an unknown mammal species. Scientists think that bats evolved from small tree-dwelling mammals that eventually developed flaps of skin between their toes called interdigital webbing. This eventually evolved into wings that not only allowed them to glide from tree to tree but actively generate lift like a bird and fly.

Beneath the umbrella of divergent evolution, there are microevolutions that can lead plants and animals down an evolutionary path that intertwines with one another. Known as coevolution, this phenomenon occurs when two species develop anatomical characteristics as a result of interactions with another species. These interactions typically centre around one of three processes in nature: pollination, parasitism and predation.

The Honeycreepers

The birds with beaks tailored to their diets

'Apapane

(Himatione sanguinea)

These narrow-beaked birds feed on plant nectar, predominantly from the flowers of the 'ohi'a lehua tree.

Kaua'i nukupu'u

(Hemignathus hanapepe)

The thin hooked beaks of these birds are used to pick out insect prey that are found beneath tree bark.

'I'iwi

(Vestiaria coccinea)

To reach the nectar of tubular flowers, these birds have evolved long curved beaks.

Maui parrotbill

(Pseudonestor xanthophrys)

Also known as a kiwikiu, these birds use their parrot-like beaks to split branches to extract insects and their larvae.

Laysan finch

(Telespiza cantans)

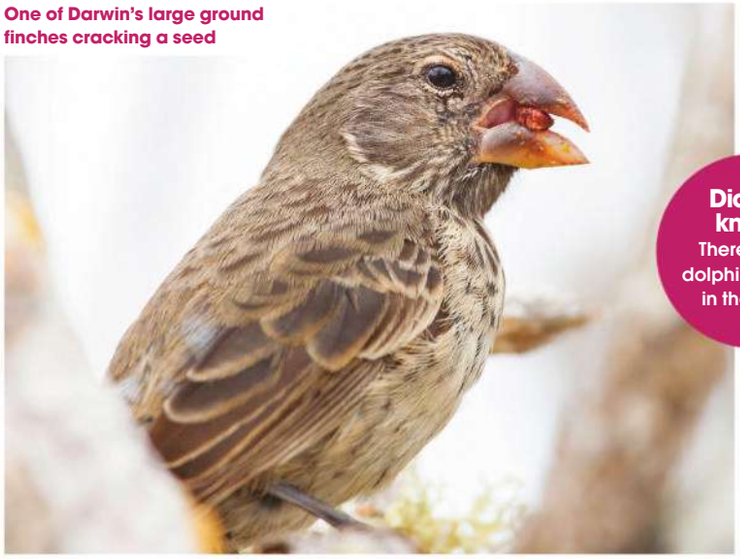
As omnivores, their beaks are used to pick fruit and seeds, as well as pick off invertebrates and even eat carrion.

Lesser 'akialoa

(Akialoa obscura)

This extinct species used its beak to hunt insects living in tree bark, inserting its entire bill into crevices.

One of Darwin's large ground finches cracking a seed



A swallowtail caterpillar looking remarkably like a green snake

Did you know?
There are 42 dolphin species in the world

© Getty / Alamy

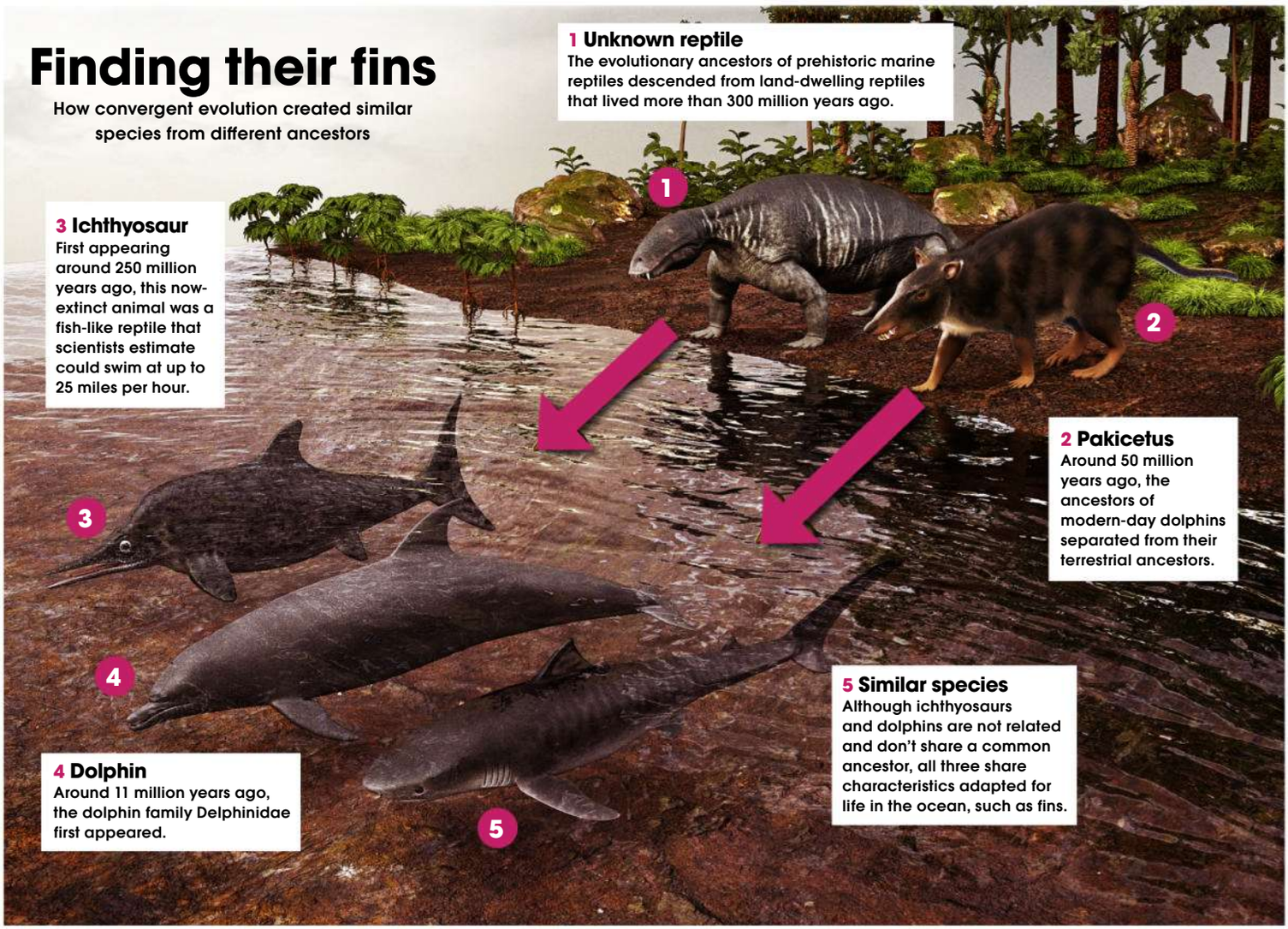
Pollinators, such as bees and birds, have evolved side by side with plant species in ways that benefit them both. For example, the pollen and nectar of the Darwin orchid (Angraecum sesquipedale) are found at the end of a long tube past its petals, which few pollinators could reach. Luckily, one pollinator, Wallace's sphinx moth (Xanthopan morganii praedicta), has evolved alongside the orchid and developed an enormous tongue called a proboscis. This can extend up to almost 30 centimetres for lapping up Darwin orchid nectar, picking up pollen along the way. It's not just the orchid that benefits – this also provides the sphinx moth with a food source other pollinators can't access.

Unlike coevolution that benefits both species, as seen in plant-and-pollinator relationships, some animals, such as Alcon blue caterpillars (Phengaris alcon), have coevolved with other species in ways that make them the perfect parasites. By mimicking the scent emitted by the larvae of Myrmica ants, Alcon blue caterpillars can infiltrate a nest and be welcomed with open arms by the ant colony, which will then care for them as their own. Studies have also shown that when a nest is under threat, the emitted scent causes ants to prioritise the protection of the caterpillars over their own larvae.

Coevolution between predators and prey provides some of the most perplexing examples of nature's ability to adapt to an environment. Typically known as Batesian mimicry, it's named after the 19th-century naturalist Henry Walter Bates and occurs when a species has evolved, behaviourally or anatomically, to mimic the characteristics of another more dangerous or venomous animal. For example, the caterpillar of the spicebush swallowtail butterfly (Papilio troilus) has evolved to present markings that bear a strong resemblance to the head of a smooth green snake (Opheodrys vernalis).

The purpose of displaying such a visual deception is to fool potential predators into believing that they are not the prey the predator might have hoped for, and are instead a dangerous animal that they don't want to interact with. The appearance of the spicebush swallowtail caterpillar wouldn't have the same effect without the existence of the smooth green snake, and thus the result of the snake's evolution has had a direct impact on the evolution of the spicebush swallowtail, as it needs to be a convincing enough mimic to deter predators.

Did you know?
Animal pollination evolved 99.6 to 65.5 million years ago



Surprising coevolution

Amazing examples of how two species have steered each other's evolution

The large eyes of a slow loris resemble the markings on a cobra's head

Slow loris and cobra

These furry tree climbers are surprisingly similar to snakes and have evolved to mimic some of their notable traits. The slow loris is one of the only known mammal species to produce venom for defence, which it secretes from a gland in its elbow and then licks to create a venomous saliva in its mouth that coats its teeth. When threatened, the slow loris hisses and will cross its arms over its head, making its face, complete with large eyes, resemble the shape and markings of a cobra.

A scoliid wasp mistaking a mirror orchid for a female wasp

Mirror orchid and scoliid wasp

In the interest of pollination, the mirror orchid (Ophrys speculum) has evolved an unusual petal that attracts male scoliid wasps (Dasyscolia ciliata). The petal, known as a labellum, closely resembles the furry brown bodies of female scoliid wasps. Tricked into thinking he's found a mate, the male wasp lands on the flower's imitation in hope of reproducing. Instead, the male wasp finds itself with a head covered in pollen as it rubs against the plant's anther, an organ that contains pollen. The wasp will then pollinate another mirror orchid when it once again mistakes its petals for another potential mate.

Fig wasps emerging from their eggs inside a fig

Wasps inside figs

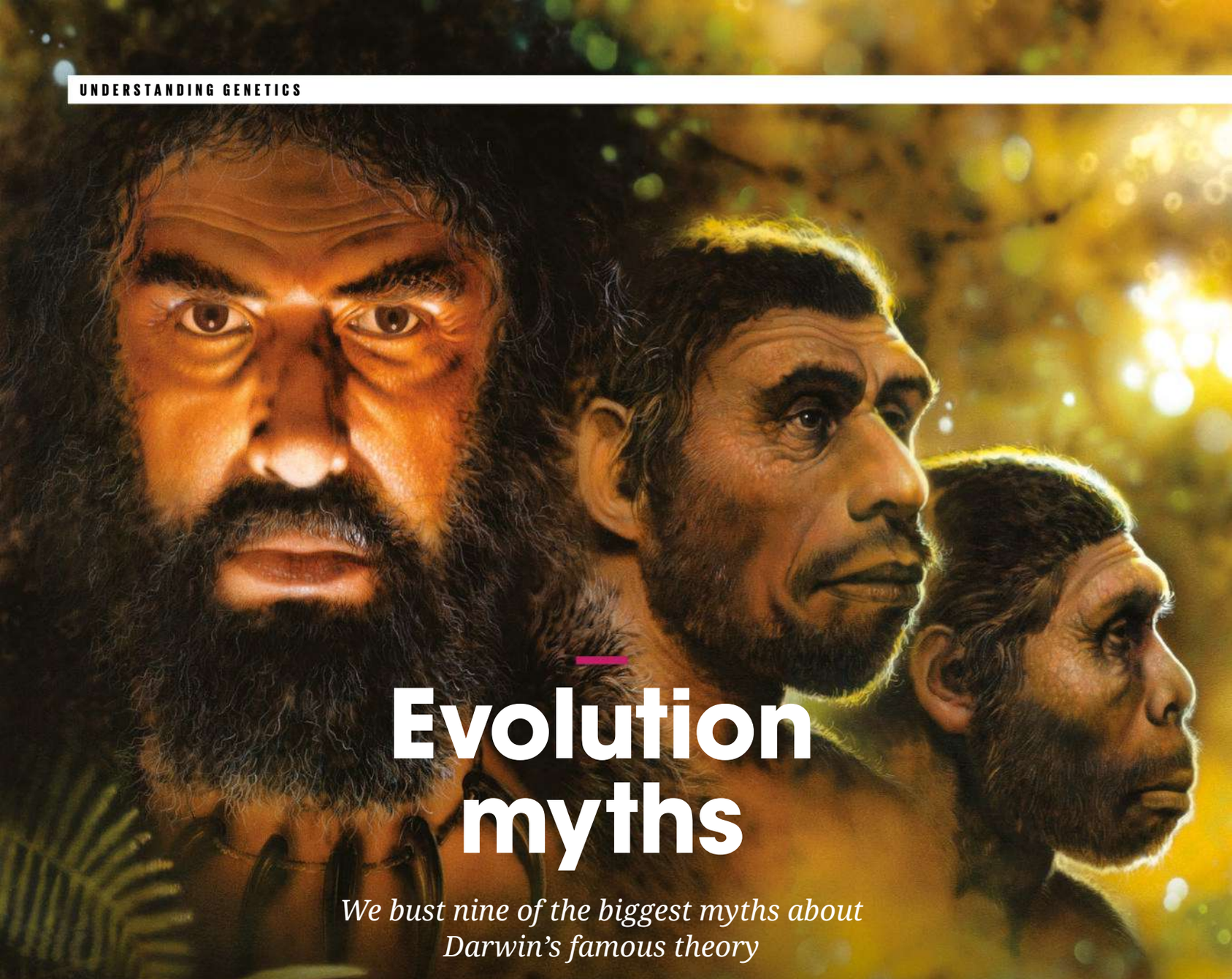
Figs produced by the fig tree (Ficus carica) are known as an inflorescence, not a fruit, where the inside of its bulbous body is full of clusters of small flowers and seeds. With its flowers on the inside of the fig, its only pollinator, a queen fig wasp (Eupristina verticillata), burrows into the fig's outer flesh and lays her eggs within before ultimately dying and being digested by the fig for nourishment. When the wasp's offspring hatch, the females gather pollen from inside the fig and take it to the next fig, where they will eventually lay their own eggs.

Cuckoo eggs are slightly larger than those in a warbler's brood

Cuckoo egg imposters

The common cuckoo (Cuculus canorus) is one of the worst parents in nature – mainly because as soon as the opportunity presents itself, female cuckoos will ditch their eggs in the nests of other birds for them to raise as their own. The presence of the Trojan egg is unknown to the host parent because cuckoos have evolved an egg colouration and speckled appearance that resembles the eggs of many other bird species, such as warblers, wagtails and pipits. The new host parent will raise the new addition until it's ready to fly the nest and continue the parasitic cycle.

© Alamy / Getty / Illustration by Nicholas Forder



Evolution myths

We bust nine of the biggest myths about Darwin's famous theory

Evolution is one of the most significant scientific ideas. It describes how species change over time or diverge to create descendant species. It explains how humans became so smart, why giraffes are so tall, and how bacteria can develop antibiotic resistance in days.

The race to explain the web of life started in earnest in the 1800s. For decades, naturalists were fascinated by the similarities between different animals – and during the 19th century, more and more ancient fossils were pulled from the ground. Scientists were beginning to reveal that the planet was much older than previously thought. It became clear that humans hadn't been around for all that long and that huge animals had once lived but were now extinct.

A naturalist called Jean-Baptiste Lamarck recognised that different species appeared to suit their environments. He proposed that they did this by adapting throughout their lifetimes and then passing on these changes to their offspring. He famously thought that giraffes acquired their long necks by constantly stretching to reach the tallest trees for food, and those that stretched more would have longer-necked offspring.

Although Lamarck's theory was flawed – it did not explain how the changes happened – he made two important observations: species could adapt to better suit their environment, and these changes were passed on to future generations.

Building on these observations, Charles Darwin published what is now known as the theory of evolution by natural selection in 1859. He proposed that rather than adapt during their lifetimes, organisms vary from their relatives and that some have traits that help them to survive longer and have more offspring. Those that were best adapted would be more likely to pass their traits to the next generation, and over a long time, the species would change.

Darwin didn't know how traits could be passed on from parent to offspring, and the theory caused controversy. However, later, we discovered that genes were the vehicles that passed information between generations and that tiny changes in the genetic code provide the small variations that drive evolution. We have traced genetic trees, uncovered countless fossils, and watched evolution happening in real time – both in the wild and in the lab.

The theory of evolution has developed to become one of the key pillars of biology. Yet, it is one of the most misunderstood areas of science. How do we know it happened if there are gaps in the fossil record? Why is it called a 'theory' if scientists know it is true? And why haven't all monkeys evolved into humans? Let's bust the myths surrounding Darwin's landmark theory.

Myth: We are descended from monkeys

So why haven't all monkeys evolved into humans?

This is perhaps one of the biggest misconceptions about evolution – that humans are descendants of modern monkeys or apes. It may be that the well-known 'evolution of man' image, showing a series of apes that become ever-more upright and human-like, has helped to spread this myth.

Monkeys and apes are not the same thing. Modern monkeys are divided into New World and Old World monkeys, both of which are separate groups of species to apes. The apes are then divided again into lesser apes (gibbons) and great apes – which include humans. So we aren't descended from monkeys, but what about apes?

We share many traits with the other great apes – chimpanzees, orangutans, bonobos and gorillas – and they are our closest living relatives. But they're not our ancestors, either. Each of the great apes, including humans, evolved independently from a 'common ancestor'.

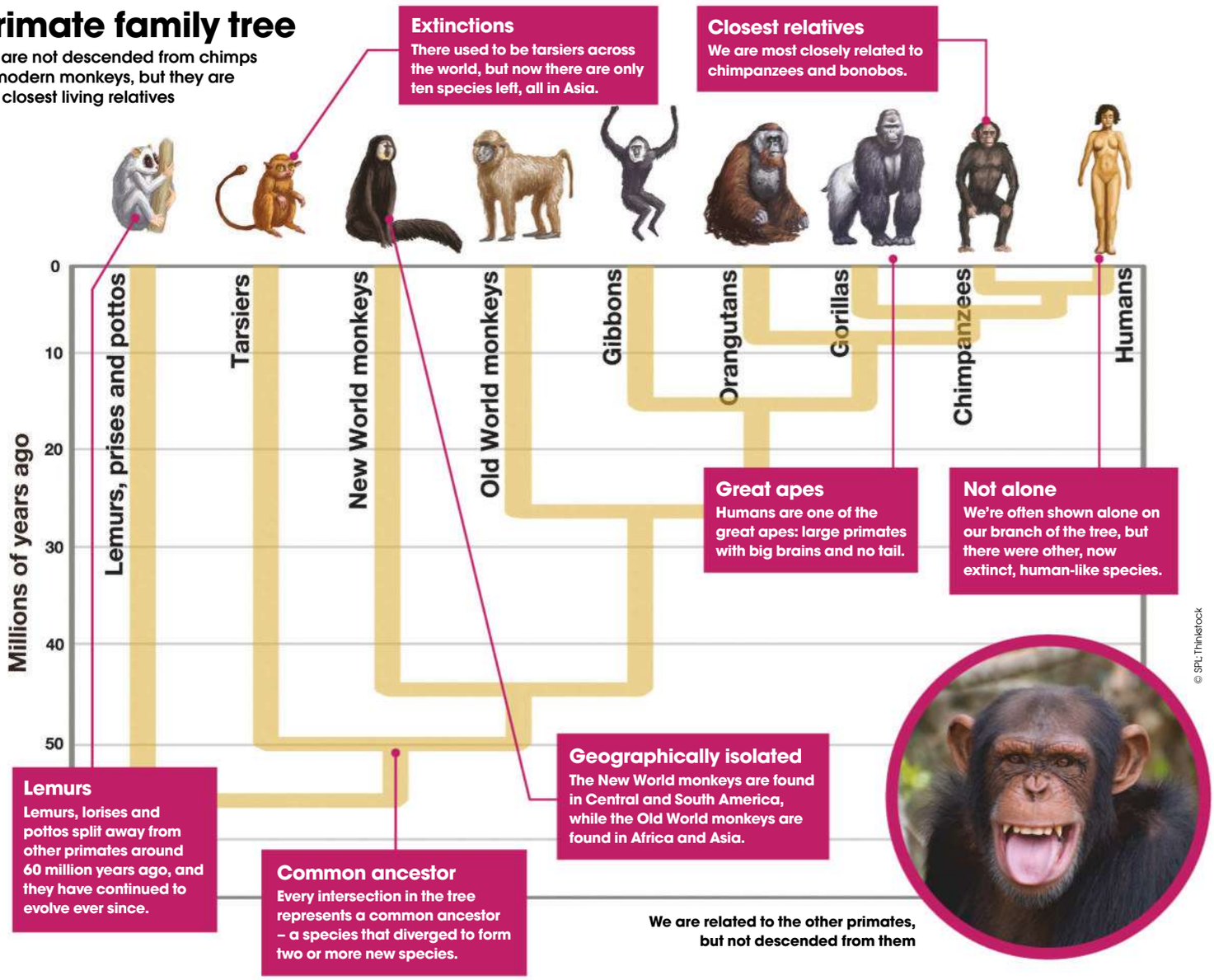
If you trace human fossils back, they gradually become more and more ape-like, with bigger teeth, smaller brains and stockier limbs. And if you trace chimpanzees back, they become more like that common ancestor, too. If you go back millions of years, the evolutionary history of humans and chimpanzees eventually converges, and you find that we share a relative that was a different species entirely – our common ancestor.

Every intersection in an evolutionary tree represents a common ancestor. If you trace back even further, you will eventually find a common ancestor between apes and monkeys, between all primates, between all animals and so on. Each branch of the evolutionary tree continues to evolve, producing new species of all sizes, shapes and colours.

"Each of the great apes, including humans, evolved independently from a common ancestor"

Primate family tree

We are not descended from chimps or modern monkeys, but they are our closest living relatives



We are related to the other primates, but not descended from them

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Myth: You can't test evolution

It happens so slowly that it's impossible to prove

Evolution usually happens over millions of years, so we can't hope to see anything as dramatic as dinosaurs evolving into birds. The trouble with tracking evolution is that genetic changes must be passed on for generations before the effects become obvious. If animals live a long time, it's hard to watch them evolve before our eyes. But that doesn't mean we can't see evolution happening in real time.

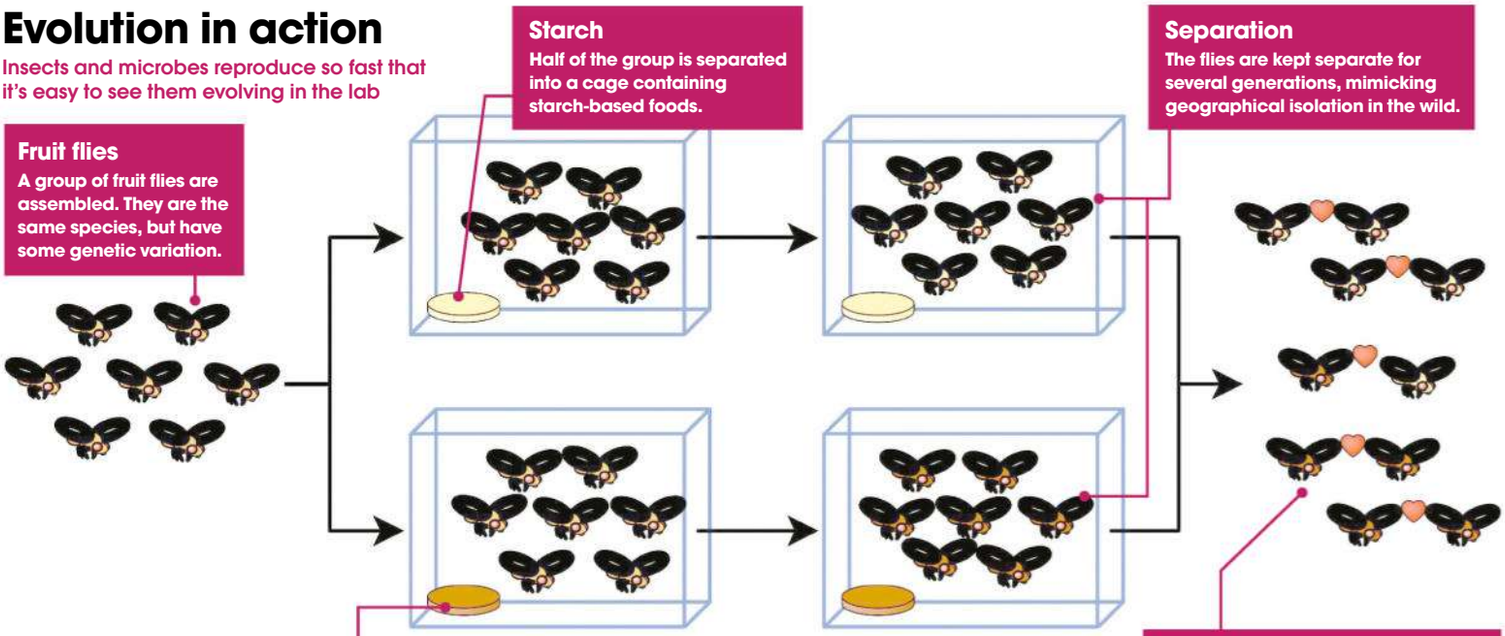
During the Industrial Revolution, Britain went through a rapid period of environmental change. Factories churned out soot, coating the trees. Peppered moths had previously used birch trees for camouflage, and it was an advantage to be pale because dark moths stood out against the bark and were quickly spotted and eaten by birds. But, once the soot came, being darker became an advantage. Quickly, the number of darker moths grew as they survived and passed on their useful genetic trait.

If you want an example close to home, we have been simulating evolution with dogs for centuries. We choose which traits we like and only breed the dogs that exhibit them – hounds are selected for scent and sight, herding dogs have double coats that shield them from the weather, and bulldogs are favoured for their flat faces. This trend is still happening today, and you only have to look at health problems with pure breeds to see the effects in action.

Selective breeding has created many different dog breeds

Evolution in action

Insects and microbes reproduce so fast that it's easy to see them evolving in the lab



> "Evolution has no goal at all, and the results are far from perfect"

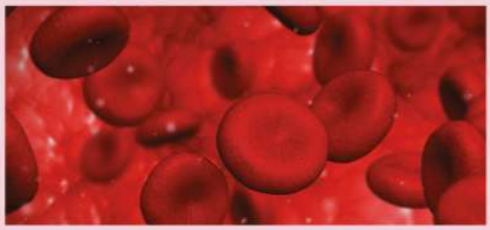
Myth: Everything is an adaptation

All traits have an evolutionary purpose

It's tempting to imagine that there is a story behind every trait, but not everything is an adaptation. Much of what you see today happened by chance or as a side effect of something else. Others are just remnants of traits that used to be useful but are not needed any more. Evolution often involves trade-offs and compromises, and it is constrained by the adaptations that an organism already has.

Chance mutations

Many traits don't have an obvious reason or advantage and aren't an adaptation. For example, around 25 per cent of the human population are 'supertasters', with far more taste buds than others.



Side effects

Some traits are side effects of others. The colour of our blood isn't an adaptation; instead, it is a side effect of the molecule that transports oxygen – haemoglobin just happens to be red.

Myth: Evolution explains the origins of life

If evolution explains how life has changed, surely it should explain how it all began

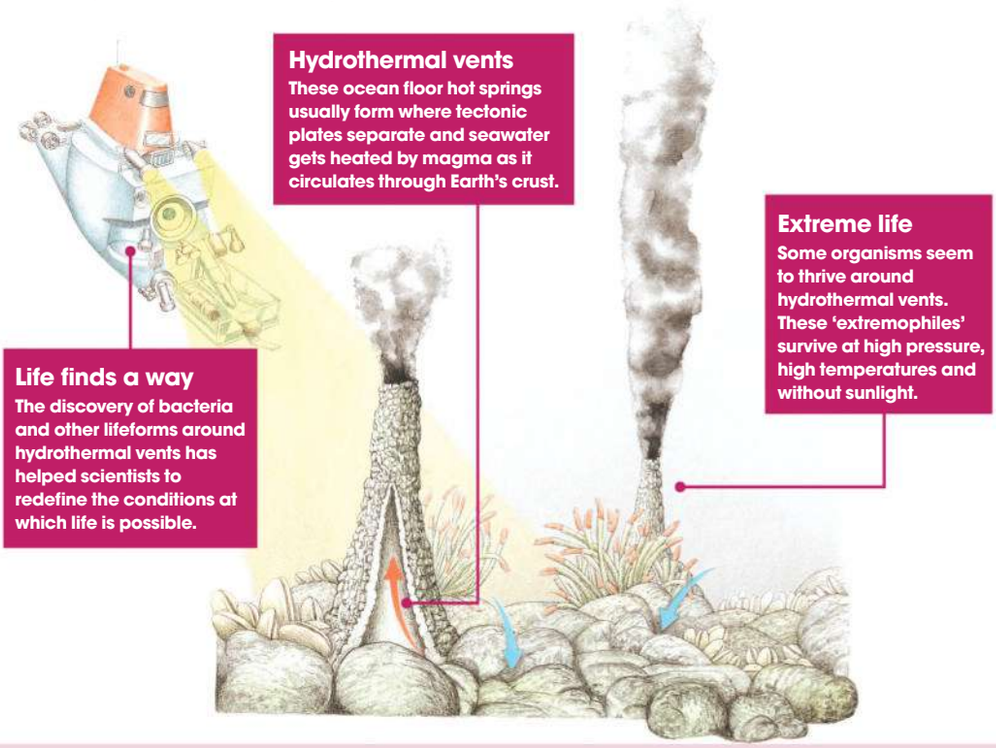
Evolution can tell us a lot about why life is the way it is and how life changes and adapts over time, but it doesn't claim to explain how it started.

Evolution has taken us back to LUCA: the Last Universal Common Ancestor – the organism from which all life on Earth evolved. Comparing the genes of organisms in the two most ancient branches of the tree of life (archaea and bacteria), it's estimated LUCA lived around 3.8 billion years ago and had at least 100 genes.

Evolution can give us clues about what was required for life to begin, but this puzzle has not yet been solved and is being tackled by scientists across many fields.

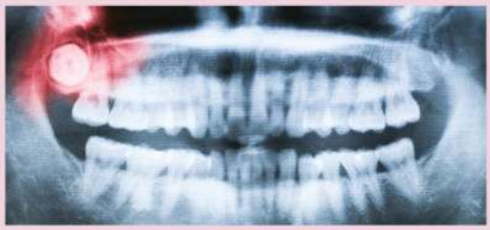
Primitive life

One of the most compelling ideas is that life began in the warm, mineral-rich waters of hydrothermal vents



Multipurpose genes

Many genes have more than one function (known as pleiotropy). For example, these curly-feathered chickens have one gene change that affects their digestion, body temperature and egg laying, as well as their feathers.



Vestigial traits

Some traits are left over from our ancestors and are no longer useful. Take our wisdom teeth; they were useful when our jaws were bigger and diets tougher, but now they're often just a nuisance.

Myth: Everything happens for a reason

Evolution has an ultimate goal and is trying to solve a problem

The way we talk about evolution can make it seem as though organisms are trying to evolve to be better, faster or stronger than the rest. In truth, evolution has no goal at all, and the results are far from perfect.

Evolution is ultimately driven by genetic mutations, which happen fairly randomly. Some of these variations help organisms to survive a little bit longer or have more offspring, and these useful genes are passed on to the next generation. Others make life a little harder.

The environment and conditions that organisms find themselves in dictate which of these random mutations will be useful and which won't. This could be down to the climate, predators, food availability or attractiveness to a mate. But, when the traits are selected, they make gradual changes over time with no end goal in sight.

Evolution works by trial and error, and the results aren't always as polished as they could be. For example, the human eye has a serious flaw. The blood vessels and nerves run in front of the light-detecting cells and must travel through the back of the eye to get to the brain. This creates a blind spot. It is a step-by-step process that has led to our eyes evolving, but it certainly isn't the 'best' way things could have been arranged.

Organisms don't want, try or need to evolve, they just do – and the results are amazing and unpredictable.

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Flies' eyes contain hundreds of light-sensing units called ommatidia

Myth: The eye is too complex to have evolved

Half an eye is no use, so how could these intricate visual machines have developed?

Even Darwin had trouble imagining that eyes were the product of evolution – but if you take it step by step, it makes sense.

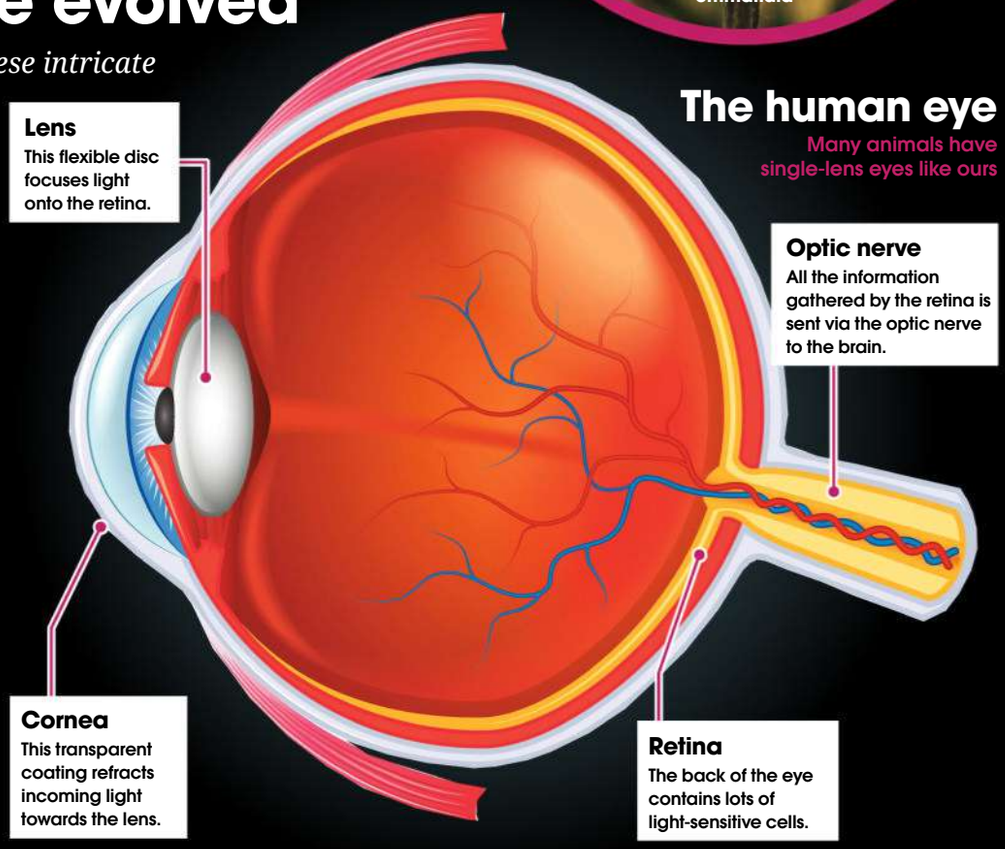
At the simplest level, eyes are spots or patches of pigments that respond to sunlight. If these pigments are on a flat surface, they only sense light and dark, but if they become dipped down into pits, they can be used to tell which direction the light is coming from.

Then, if these pits become a little deeper, and the opening starts to close over, it forms the equivalent of a pinhole camera, restricting the light coming in and producing actual images. If that pinhole then becomes covered by a layer of transparent cells, the pit can fill with fluid, allowing a lens to start to form from crystals inside. This lens helps with focusing, making the images even sharper.

Each of these small adaptations may give an organism a slight advantage in its environment, such as the ability to hunt more effectively or spot predators further away. Over many generations, an adaptation is selected, and the eye shape of the species gradually changes.

The human eye

Many animals have single-lens eyes like ours



Increasing complexity

If you look closely, simple versions of the human eye exist in the natural world

"Those with the most useful adaptations are more likely to survive and breed"

1 Spot
Single-celled organisms called Euglena have 'eyespots' containing light-sensitive pigments, which help them to detect light and dark.

2 Cup
Flatworms have spots of pigment that are buried inside cups, helping them to determine which direction the light is coming from.

3 Pinhole camera
Deeper cups with a slightly closed opening form the equivalent of a pinhole camera, allowing animals like the nautilus to see images.

4 Lens
Transparent cells cover the opening at the front of the eye, and a simple lens structure forms inside. Snails have eyes like this.

5 Complex camera
Over time, tiny improvements gradually add up to the complex camera eyes that organisms such as octopuses and humans have today.

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Myth: Aren't there gaps in the fossil record?

Missing links in fossils must disprove evolution

It would be nice if we could see neat historical lines that traced the evolution of modern species step by step, but fossils are rare. Of all of the mammal species that are currently in danger of extinction, we only know of fossils for nine per cent of them. In the future, if we were to look back, it would be like the rest never existed at all.

Fossils don't form very often. Even for those animals with the right body type, fossil formation is dependent on how and where they die. In jungles, for example, other organisms quickly devour the dead, removing all traces of their bodies. Because of this, gaps in the fossil record are inevitable.

However, new fossils are found all the time, and many 'transitional' species have been identified that do provide support for evolutionary theory. Take the horse, for instance. Today's horses have one toe, but they evolved from dog-sized ancestors with multi-toed feet. The fossil record shows several intermediate steps, showing how toes were lost, shortened and combined to form the familiar hoof that we see today.

Archaeopteryx shows the link between dinosaurs and birds, with key features of both

Myth: Natural selection drives all evolution

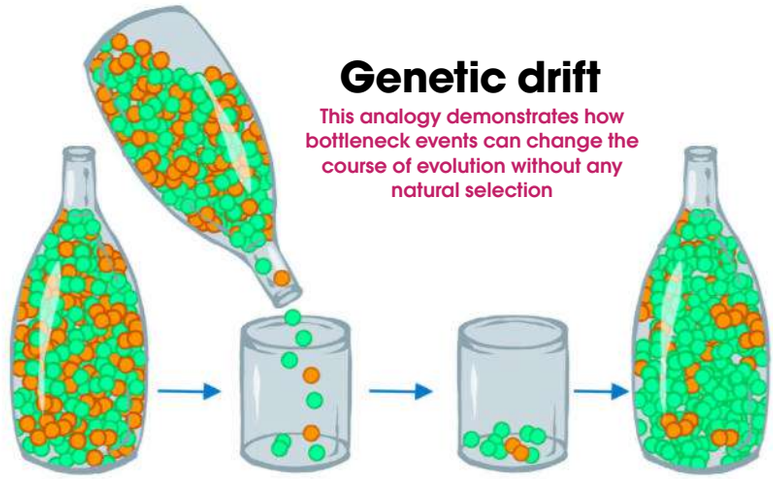
Is survival of the fittest the only way that evolution happens?

Random mutations of genes can make some individuals slightly different to others, creating genetic variation. Predators, competition and other environmental factors can pressure organisms, and those with the most useful adaptations are more likely to survive and breed, passing on their genes to their offspring. This process, called natural selection, is what Darwin is famous for describing but it isn't the only way evolution can occur.

Another mechanism is called genetic drift. Here, rather than traits being selected for, they are lost or become more common due to a random event. This can happen if populations become separated, or if some individuals are killed, particularly if the population size is small.

Genetic drift

This analogy demonstrates how bottleneck events can change the course of evolution without any natural selection



1 Original population
To start with, this population is mixed, with orange and green individuals in roughly equal proportions.

2 Bottleneck
A random event happens, such as a natural disaster, causing the population size to decrease dramatically.

3 Remaining population
Now, there are more green individuals than orange; the gene pool has changed by chance.

4 New population
As the remaining population breeds, the genes are passed on, creating a new population where green is much more common. In time, orange could be lost altogether.

Myth: Evolution is 'just' a theory

We don't know for certain that evolution occurs

This one is hard to argue with, given that the word 'theory' is right there in its title, but the real problem is the word 'just'. In science, there's no such thing as 'just' a theory.

In general conversation, the word 'theory' is used interchangeably with words like 'hunch', 'speculation' and 'belief'. It's a fuzzy way to indicate that you think something might be true, but you don't have all of the evidence to back it up. This is not the case in science.

A scientific theory is based on evidence. There are many well-established principles of science, including evolution, that are centred on theories – for instance, that Earth orbits the Sun and that living things are made of cells. They provide a comprehensive explanation of what we see and can be used to predict what might happen in the future.

The evidence for evolution is compelling, and the theory has been confirmed repeatedly in different ways. The fossil record, though incomplete, demonstrates the progression of organisms over time. This is supported by the physical, chemical and genetic similarities between living things. And there are plenty of real-life examples out there of organisms visibly changing over several generations.

Evidence of evolution is written all over our DNA

The more evidence scientists find, the more they reinforce Darwin's ideas. Evolution is not 'just' a theory, because, in science, a theory is one of the strongest arguments that can be made.

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Are fears genetic?

Your phobias could be passed down through generations in DNA

It was assumed that irrational fears are learned through personal experience or taught to us by others. However, it is now thought that some phobias have a genetic origin. For example, identical twins are more likely to share the same fears than non-identical twins, even if they are raised apart.

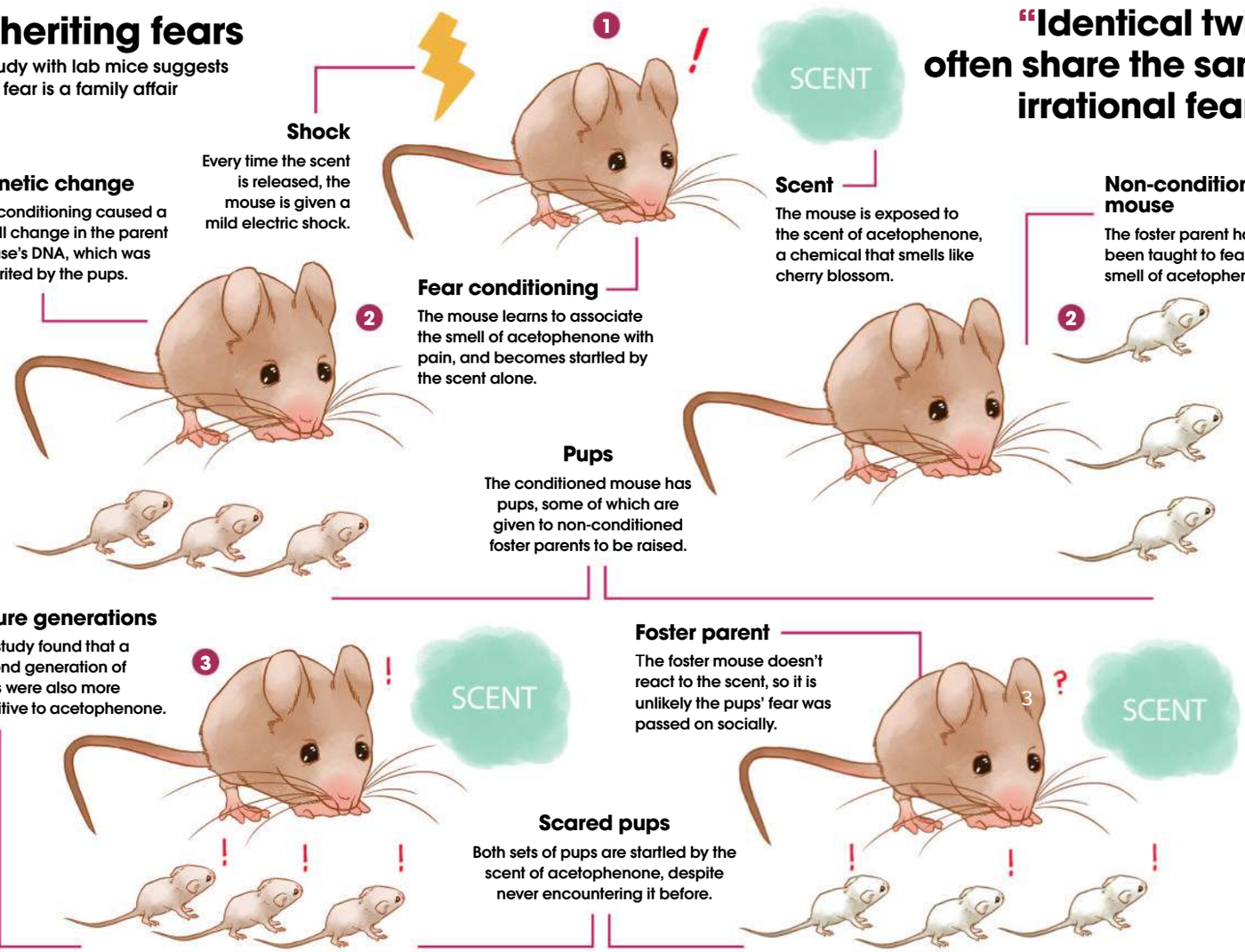
Experiments with mice have shown the fears they develop can be passed down to their children and even their grandchildren. The mice were conditioned to fear the scent of acetophenone – a sweet-smelling chemical. Researchers found that the pups, and even the grand-pups, of the conditioned mice, were startled by the scent, too.

One explanation could be that parent mice communicate with their pups to teach them what to fear. Studies have found that when mice are scared, they release pheromones that act as an alarm signal. However, in the acetophenone experiment, the pups proved to be sensitive to the scent from the first time they encountered it. What's more, some pups of conditioned mice were fostered by non-conditioned mice. The non-conditioned parents were not afraid, but the pups were, suggesting the fear's origin was genetic.

It is not clear how the conditioned fear is passed on, but the current theory is that it is down to something called 'epigenetic inheritance'. The original conditioning process leads to chemical modifications that change gene expression (which genes are switched on or off), without changing the DNA sequence. The researchers found that the conditioned mice and their offspring developed more scent receptors in their brains, compared to non-conditioned mice. With more of these receptors, they can detect the presence of acetophenone at lower concentrations and are alerted to it more easily.

Inheriting fears

A study with lab mice suggests that fear is a family affair



"Identical twins often share the same irrational fears"

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Generational memory

Do we know things before we're born based on the experiences of those before us?

Your genes make you who you are. They're inherited from your parents, and theirs from their parents before them, going all the way back to the time humans first emerged. Along the way, they've picked up traits that help us survive as a species, diversifying for humans living in different parts of the world with distinct needs and evolving along with the environments around us.

Much of this is encoded as natural instinct. When a baby is born, it doesn't need to be taught how to breathe or cry when it needs attention – this is hard-wired into our DNA. We know that when we're tired we need to sleep and when we're hungry we need to eat. The same goes for animals. Within two hours of being born, a foal attempts its first steps with little guidance from its parent, all from instinct.

As well as our basic instincts, our genetics can carry more complex abilities, knowledge and conditioning. One example of inherited behaviour exhibits itself through reflexes that keep us safe in situations where we perceive danger, such as pulling our hand back when it meets something hot or jumping when we're startled.

Findings have also hinted that our emotional responses and facial expressions could be hard-wired behaviours. Babies start to smile and laugh at around two and four months respectively – again, this isn't something they're ever specifically taught. Although they may take in the expressions and moods of those they grow up around, it's hard to test if they connect emotion to the faces they see. However, a 2009 study showed that athletes who had been born blind made the same disheartened expressions when losing as athletes with sight, suggesting that facial expressions may not be something we learn from watching others.

While genetics play a part, infants are also heavily influenced during their time in the womb. Mothers who eat strong-tasting foods such as garlic can affect the taste buds of their children, giving them an affinity for the

"Inherited behaviour exhibits itself through reflexes that keep us safe, such as jumping when we're startled"

same tastes later in life. Taste and smell are important triggers that babies look for when first feeding, as the mother's milk will carry the same flavours experienced in the womb. This pre-birth taste sampling may have developed as a way to teach newborns to feed, increasing their chances of survival. This prenatal flavour learning is also seen in other mammals such as rabbits, cats and dogs.

Whether we have a predisposition to a certain language is still something that's contested – including whether our parents' native tongue comes more naturally to us through genetics or merely from exposure. However, what is clear is that humans have a biological preparedness for learning a language, often speaking in full sentences by the age of four. Again, prenatal learning could influence this, as it's been proven that a baby can hear sounds (the part of the brain that processes these noises can become active in the last trimester).

Looking to the animal kingdom, fairy wrens also 'speak' to their eggs in this way, with the mother singing a specific song that her chicks will later chirp back to her once hatched. This is used as a way to identify each other, almost like a mother-child password. However, suboscine birds seem to have the song of their species ingrained. Chicks hatched from eggs incubated in soundproof solitude are able to produce the correct call for their species having never heard it, meaning this could be true for humans too.

Generational memory could also help explain why certain people are naturally gifted in areas such as music, sport or mathematics. It's argued that they could be unlocking knowledge stored from ancestry, tapping into the talent of generations ago. The problem is that the existence of generational memory is hard to prove, since there are so many environmental and outside factors that change behaviour and personality, especially with young minds, which are so easily moulded. However, the theory is starting to be taken more seriously, and studies involving short-generation life forms such as nematode worms are making significant breakthroughs. We may soon have undeniable proof that our genetics pass down more than we think.

It's not just visual traits that are passed down from parent to child

Inherent animal behaviours

How fear was shown to be passed down through generations of mice

In a 2013 study to explore if phobias and anxiety can be transferred genetically, neuroscientists from Emory University in Atlanta, Georgia, trained male mice to fear the scent of cherry blossoms by associating it with a mild shock. These mice were then bred, and their offspring were raised without ever being exposed to the smell. Upon reaching adulthood the second-generation mice were introduced to the same smell. Despite never experiencing the shock themselves, the scent alone was enough for them to exhibit signs of anxiety and fear. It was also discovered that their noses had more neurons specifically designed to detect this scent, as well as more brain space dedicated to recognising it. So this wasn't just a behavioural change – it was physical, too.

Even more surprising was that when these mice were bred, the grandchildren of the original mice exhibited a similar reaction to the scent. The experiment confirmed that genetic markers could be used to transmit a traumatic experience to future generations. We acquire these epigenetic markers throughout our lives by learning and interacting with our environment. Teaching the next generation what to be fearful of without them experiencing the trauma could help the survival of a species.

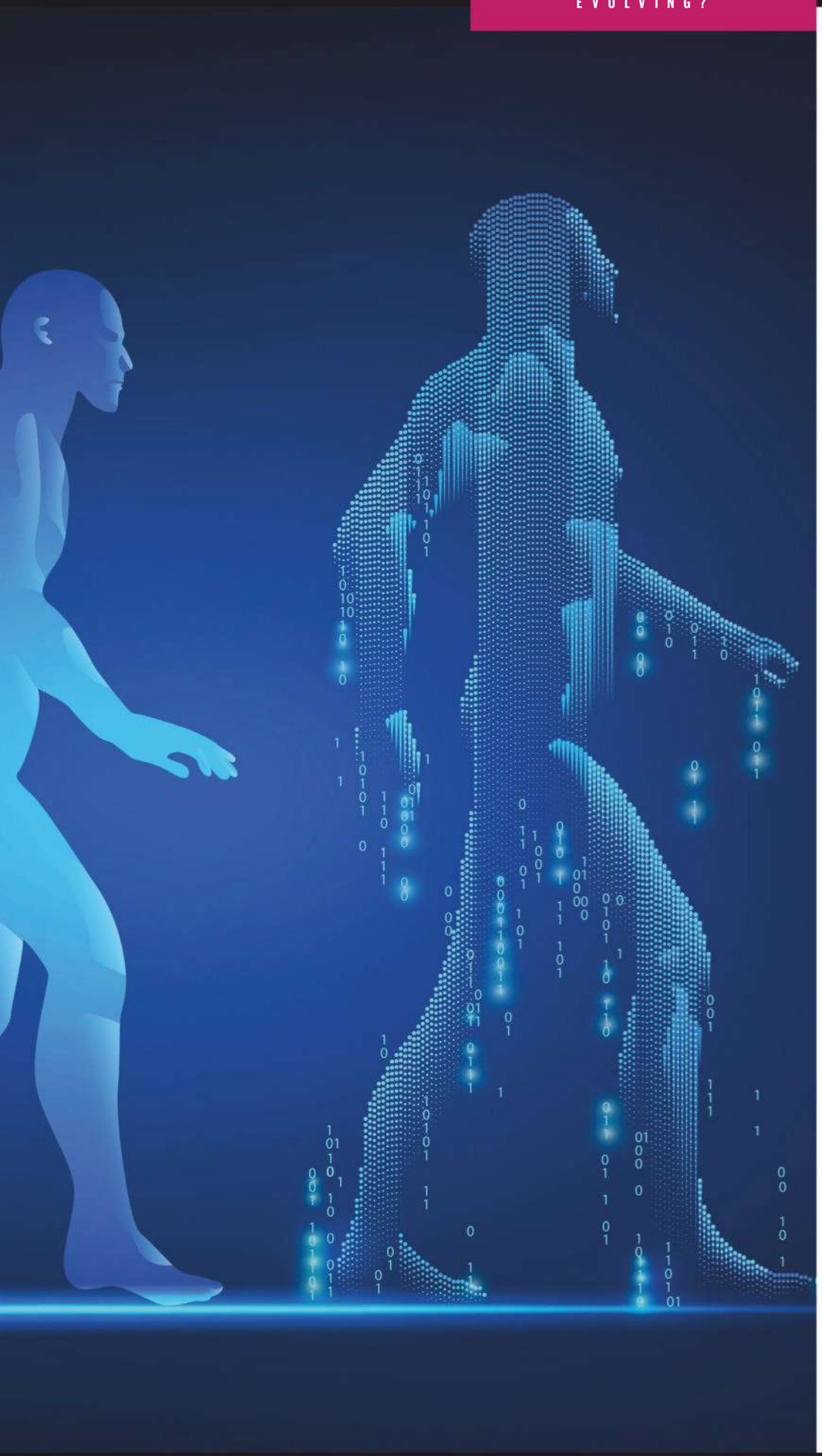
Mice have amazing memories and are known never to forget a route once they've memorised it

© Getty Images

Are we still evolving?

Have culture and technology stopped evolution in its tracks?

EVOLUTION



Every human alive today can trace their ancestry back to East Africa around 200,000 years ago – DNA from a single woman still exists in every one of our cells. At the time, the human population was tiny, and her descendants are the only ones still alive today. They spread across the continent 100,000 years ago before radiating out in waves across the world. Scientists know the mother of humanity as mitochondrial Eve.

We may have dispersed, but the genetic differences between us are surprisingly small. There is no major distinction between people living on different continents or people of different races. In fact, there are more genetic differences between subspecies of chimpanzee. This similarity makes people question whether we've stopped evolving completely.

Evolution relies on a few key ingredients. Every generation, an organism makes more individuals than are able to survive. There are differences between those individuals, known as phenotypic variation. The cause of those differences, genes or genotypes, are heritable, meaning that they can pass from one generation to the next. Some traits are better suited to the current environment than others. Individuals with those traits are more likely to survive and reproduce, passing the genes for their traits on to the next generation.

New traits enter populations in three main ways, the most well-known of which is mutation. When we make sperm or eggs, cells in our reproductive organs copy their DNA. This process is error-prone, so every time it happens

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Evolution depends on changes in culture and science

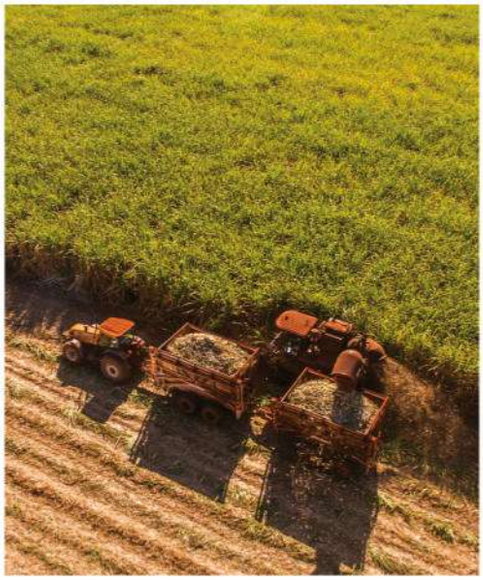
mistakes creep in. This creates tiny changes in the genetic code that pass to the next generation. For the most part, the differences don't do anything useful – or harmful. The mutations are often silent (they do nothing) or neutral (they do something, but it doesn't make a difference). In fact, many mutations aren't even in genes; they're in the DNA that sits between them. However, sometimes mutations change the way a gene works.

New traits can also enter populations via gene flow. This happens when groups of people separate and then come back together, sharing new genetic information. Finally, traits change because of sex. Babies inherit genetic material from both parents, putting new combinations of genes together.

Over the past 100,000 years, these three mechanisms have changed the traits that make us human, but we are still young in evolutionary terms. We take a long time to reproduce, and there's a limit to the amount of variation that can accumulate in a few hundred thousand years. Your genetic information only differs from someone else's by around 0.1 per cent, and most of those differences are single-letter changes. Despite outward appearances, the whole human population still shares close family ties.

Our genes are always changing, but genetics is just one piece of the evolutionary puzzle. Our environment has a huge role to play in how our species evolves. For new traits to pass from generation to generation, they need to change our chances of survival. This is where Darwin's natural selection comes in. If a genetic change makes an individual more likely to reproduce they have a better chance of passing on their genes. We know this as 'survival of the fittest', but it's not always about being the biggest, strongest or fastest. It's about having traits that let you make the best use of your current environment. As the environment changes, so do the kinds of mutations that might be useful.

This is where human evolution gets complicated. We can change our environment with culture, science and technology, messing with natural selection. If you look deep into history, our human-like ancestors were at the mercy of their environment.



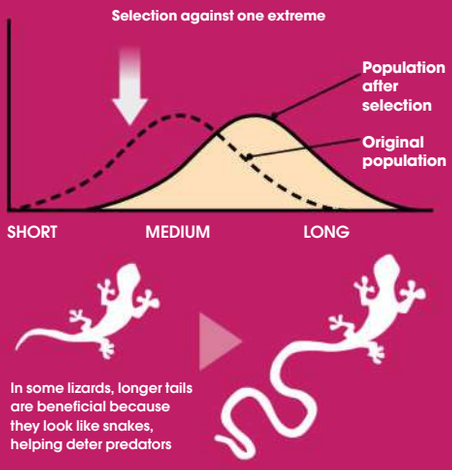
"As the environment changes, so do the kind of mutations that might be useful"

Types of selection

Three laws of natural selection govern evolution, but other selective factors can play a role

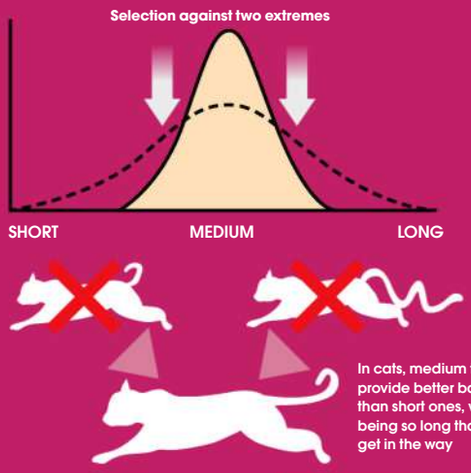
Directional

If the environment changes, it forces organisms to adapt. Directional selection pushes traits in one direction, towards a new solution. Once they find the solution, traits can stabilise again, unless the environment keeps shifting.



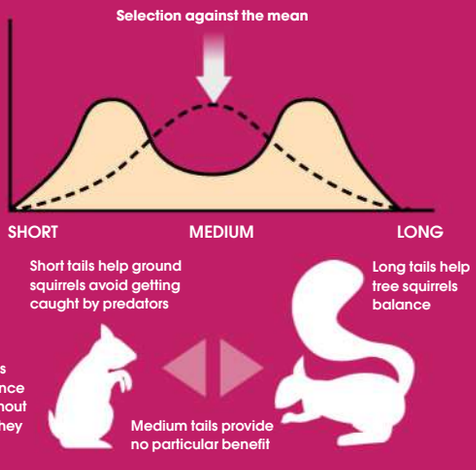
Stabilising

Stabilising selection encourages organisms to keep the same traits. This tends to happen when the environment is stable and the organism is already well-adapted. Any changes make them less fit and therefore less likely to pass on their genes.



Disruptive

Sometimes, there is more than one way to adapt to a change in the environment. In these situations, organisms evolve away from the middle ground and towards one of two extremes. If this persists, a population may split into two new species.



Sexual

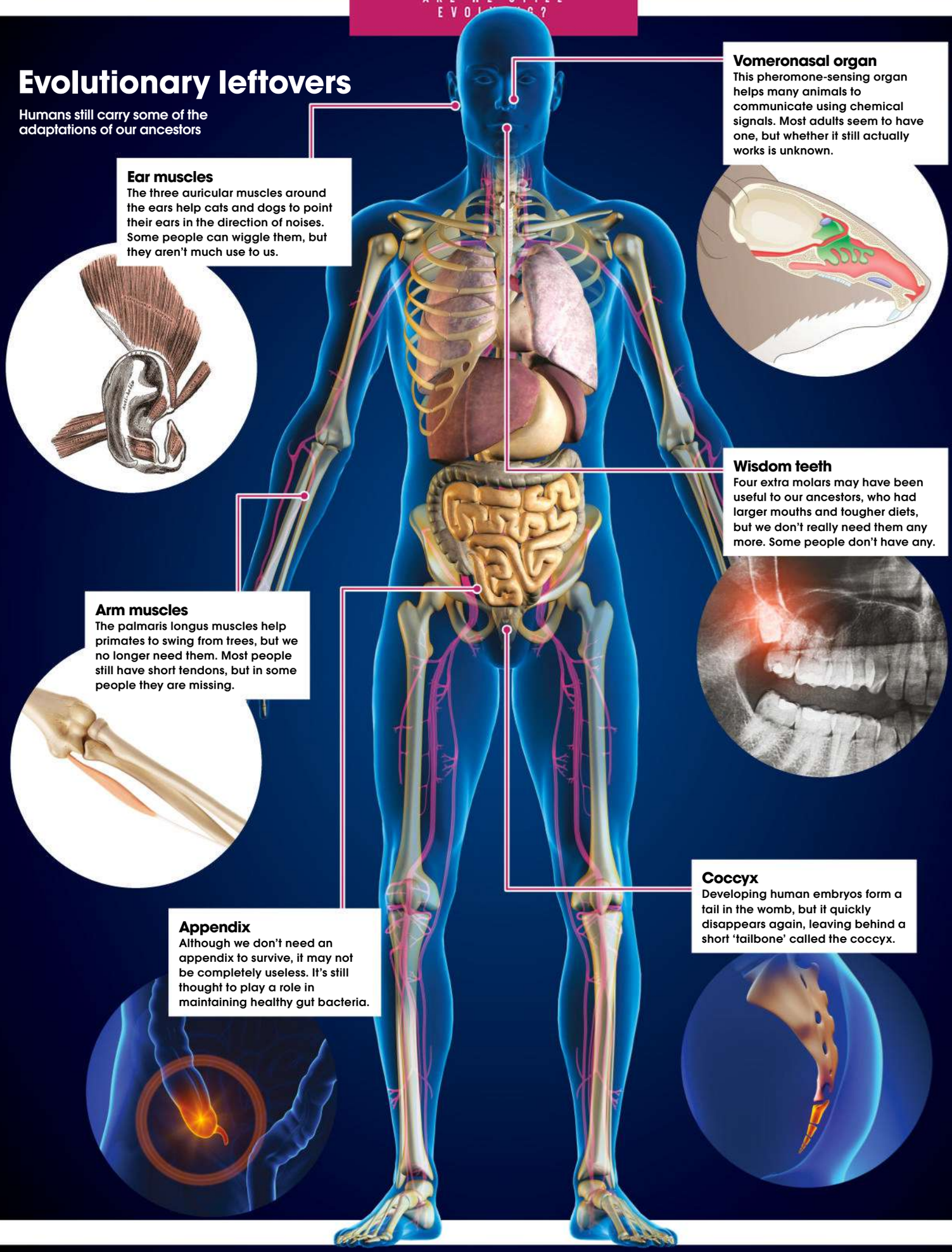
Natural selection favours animals best suited to their environment, but it's not the only way. Sexual selection favours traits that make individuals more attractive and more likely to reproduce, even if they don't help them to survive.

Artificial

Artificial selection works in the same way as natural selection, except that we make the decisions. By choosing which animals to breed, we dictate which traits are passed on to the next generation.

Evolutionary leftovers

Humans still carry some of the adaptations of our ancestors



Ear muscles

The three auricular muscles around the ears help cats and dogs to point their ears in the direction of noises. Some people can wiggle them, but they aren't much use to us.

Vomeronasal organ

This pheromone-sensing organ helps many animals to communicate using chemical signals. Most adults seem to have one, but whether it still actually works is unknown.

Wisdom teeth

Four extra molars may have been useful to our ancestors, who had larger mouths and tougher diets, but we don't really need them any more. Some people don't have any.

Arm muscles

The palmaris longus muscles help primates to swing from trees, but we no longer need them. Most people still have short tendons, but in some people they are missing.

Coccyx

Developing human embryos form a tail in the womb, but it quickly disappears again, leaving behind a short 'tailbone' called the coccyx.

Appendix

Although we don't need an appendix to survive, it may not be completely useless. It's still thought to play a role in maintaining healthy gut bacteria.

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Lucy, a famous fossil of a species known as Australopithecus afarensis, lived 3.2 million years ago. She had ape-like characteristics, including a large jaw, long arms and a covering of fur, but she walked on two legs. She lived in the trees like other apes, but the environment was changing – trees were disappearing, and Lucy was spending more time on the ground. Eggs found near her remains suggest she might have been foraging.

Between Lucy and mitochondrial Eve, climate change eventually forced our ancestors out of the forests and onto the plains. They had to run under blazing sunshine to survive, and body hair became a burden. Bare skin and the ability to lose heat by sweating became an advantage. Pressure from the environment pushed the genes of our ancestors to change.

Over time, early humans evolved bigger brains, smaller jaws and complex social structures. We harnessed fire and invented tools, and as we became more intelligent, we made more and more changes to our environment. This changed everything.

The advent of agriculture around 10,000 years ago caused a seismic shift in human history. Suddenly, we could produce our own food on demand, right next to our homes. DNA from ancient humans has revealed that changing our own environment changed at least 12 regions of our genetic code.

Researchers at Harvard Medical School examined the remains of 230 people who lived between 8,500 and 2,300 years ago. They found differences in genes involved in height, metabolism and skin pigmentation. Around 4,000 years ago, a mutation appeared that allowed adults to keep digesting milk. Light skin became more common, which the researchers believe may have been a response to less vitamin D in a plant-based farmer's diet. The immune system also changed, which may have helped people to live closer together.

We share behaviours that we learn during our lifetimes, passing information from generation to generation like genes. Learning and culture change our environment, adapting to the pressures that drive selection. This kind of genetic and cultural co-evolution isn't unique to humans. Whales and dolphins are some of the most intelligent animals on the planet, and there is evidence that they also evolve in response to learning.

Killer whales can tackle many different types of prey, but certain groups prefer different meals. In the North Atlantic, for example, some like salmon, some prefer mammals and others eat sharks. These cultural preferences pass from mother to baby, and because the groups don't tend to mix, they stay the same across generations. Scientists found differences in the genetics of whales that eat fish versus those that eat mammals. We changed our genes by learning to farm, and they've changed theirs by choosing which prey to eat.

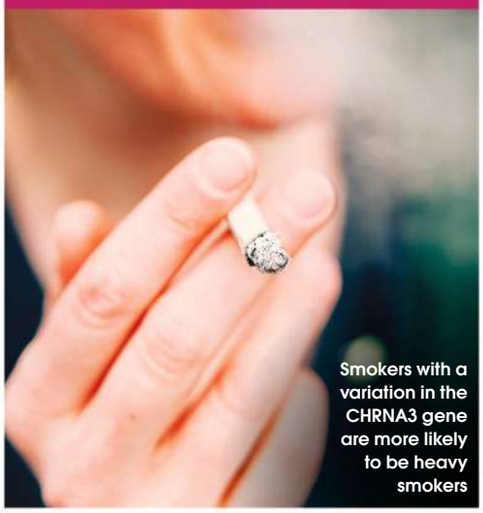
This cultural learning helps us to keep adapting, but humans have taken it further than any other animal. We made clothes and complex shelters. We domesticated plants and animals to provide a steady source of food. We built boats, cars and planes to explore the world. We invented medicine to treat injuries and diseases. We made it possible to choose when – and if – to have children. We can

Ongoing evolution

Two studies have found evidence to suggest that we are indeed still evolving, albeit very slowly. Among smokers, those with a variant of a gene known as CHRNA3 are associated with smoking more heavily than average.

Being a heavy smoker increases the risk of dying from a smoking-related disease, such as lung cancer. Scientists found that, between generations of 80-year-olds and 60-year-olds, the variant of this gene has decreased by about one per cent. However, until further data is collected from the younger generations, this trend cannot be confirmed.

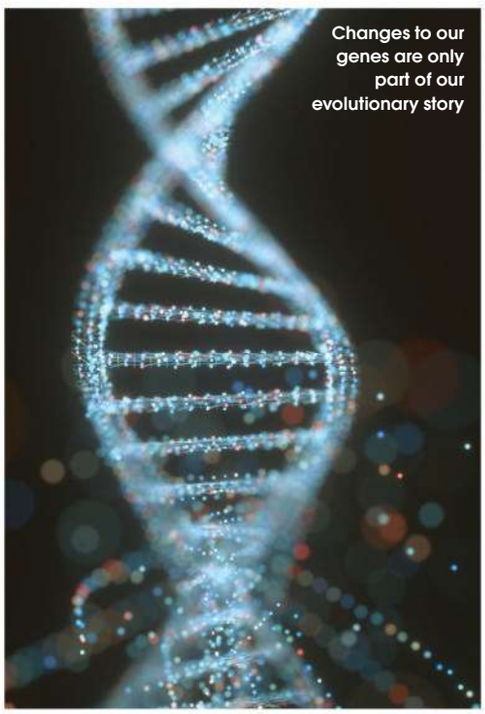
A similar decline seems to be emerging in those with a variant of the gene ApoE4, which increases the risk of developing late-onset Alzheimer's and cardiovascular disease. One possible explanation for both these gene variants becoming rarer is that more people are having children later. The number of people waiting until their 40s or 50s to start a family is increasing, but this is also the age at which people with such gene variants may be at risk of dying.



Smokers with a variation in the CHRNA3 gene are more likely to be heavy smokers

The jaws of humans and chimpanzees reflect our different diets

The development of technology will continue to shape the future of our species



Changes to our genes are only part of our evolutionary story

"Cultural learning helps us to keep adapting"

even survive in space. We have secured our environment, reducing the pressures that push other species to change over time. Reducing those pressures freed up even more time for new ideas and new technologies. Science has made it possible to change our environment more than ever before, but does that mean that we've stopped evolving?

It's hard to see evolution in action in human populations today because we have such a long lifespan, and even when natural selection isn't happening, our genes continue to mutate, a phenomenon known as genetic drift. However, there is one serious selective pressure that we still don't have under control: disease. If you look into our past, you can see how modern humans have changed in recent years.

The plague ripped through Europe around 750 years ago, killing vast numbers of people. When our species faces diseases we can't yet treat, natural selection takes over. Scientists think that's why modern populations in Northern Europe have a higher frequency of a mutation in a gene called CCR5. This gene codes for a molecule used by the immune system, and it provides protection against the plague bacteria, Yersinia pestis. It also protects against HIV. People with the protective trait were more likely to survive, and their descendants are still alive today.

As a species, we have outsourced huge parts of our survival to technology. We control our environment to maintain a steady state, reducing the pressure that forces genes to change, but to keep this going we need our environment to stay the same, and we haven't worked it all out yet.

What happens when the climate changes, or when antibiotics no longer work as they should? We have buffered ourselves against natural selection for the moment, but we haven't out-evolved evolution.

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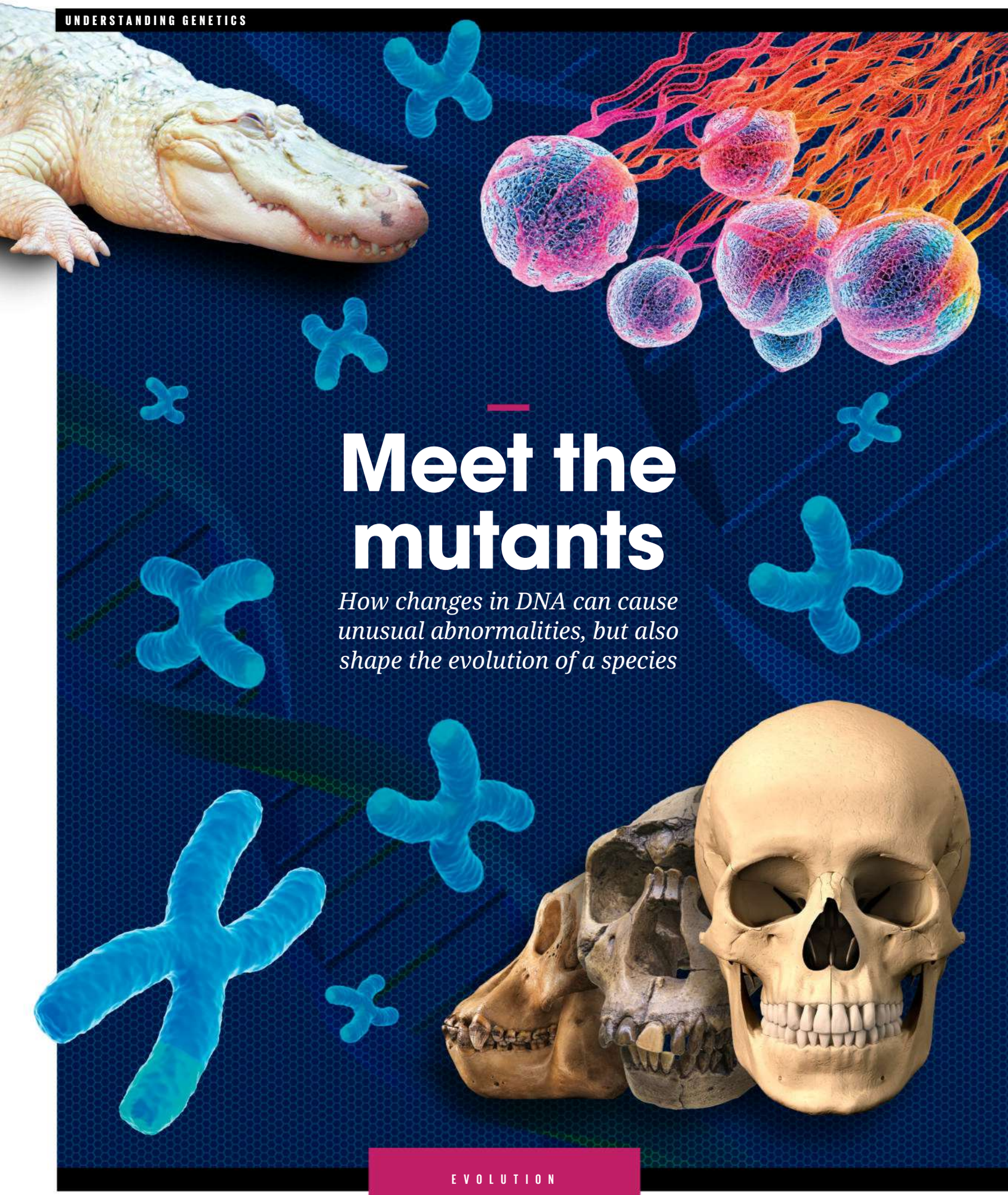


Meet the mutants

How changes in DNA can cause unusual abnormalities, but also shape the evolution of a species

EVOLUTION

What makes you who you are? It's a molecule called deoxyribonucleic acid, better known as DNA. This omnipotent molecule is made up of twisted strands of sugars and phosphates, creating its double-helix shape. Connecting the twisting strands are four bases known as nucleotides: adenine, cytosine, guanine and thymine. The sequence in which these bases find themselves along each strand of DNA is what ultimately determines the development and function of an organism.

The way DNA works is similar to the way a computer reads binary code. A molecule of DNA is divided by varying lengths of base sequences called genes. Some genes contain hundreds of bases, others millions. Each gene acts as a set of instructions to program an organism, controlling what it looks like, how its body functions and even how it behaves. The complete set of genetic information in an organism is known as its genome. The human genome is held in 23 pairs of chromosomes, long bundles of DNA which sit inside the nucleus of a cell. The size of an organism's genome varies across the spectrum of life – for example, a fruit fly has only four chromosome pairs, while a dog has 39.

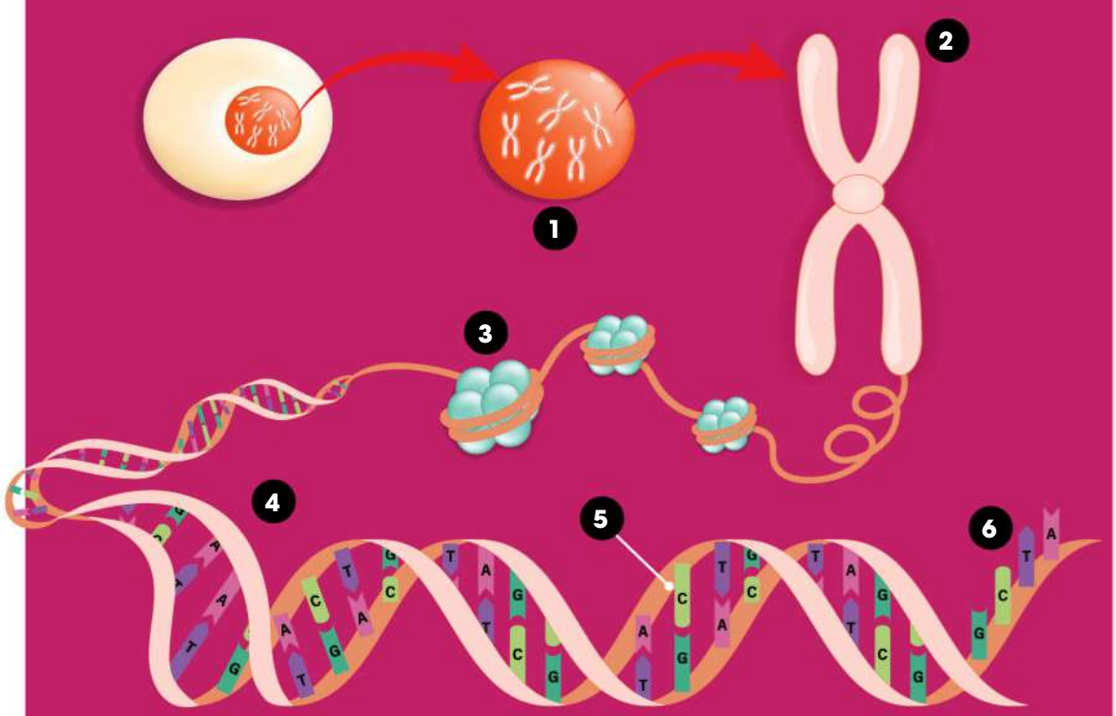
Did you know?
Down's syndrome is caused by a chromosome mutation

There are two important distinctions within a DNA molecule: genes that are referred to as coding genes and non-coding genes. Around one per cent of DNA is made up of coding genes, which actively supply the information for the production of proteins. Proteins are vital molecules that act as the raw ingredients to grow and develop an organism. The remaining 99 per cent of DNA is made of non-coding genes; these don't provide the blueprints for protein production but can influence how proteins are made and even prevent production.

Like lines of computer code, when nucleotide sequences within a gene are changed, deleted or swapped, an organism's biological program is altered. This is known as a mutation. Mutations can be split into one of three categories: silent, missense and nonsense. Silent mutations are, as the name suggests, an alteration of nucleotides that have no protein production. Missense mutations, on the other hand, will alter the function of a protein. Finally, nonsense mutations cause proteins to be nonfunctional. Mutations occur during the time the cells of an organism divide and grow. During cell division, all the DNA information within the nucleus is unzipped and exactly copied to create a perfectly functioning replica. However, on some occasions, the genetic duplication isn't exact –

Unravelling DNA

The genetic world that's held within our cells



1 Nucleus
This is the location in the cell where all an organism's genetic information is held.

2 Chromosomes
Within each cell nucleus are 23 bundles of genetic information that are called chromosomes.

3 Histones
These basic proteins support the structure of a chromosome.

4 DNA
The structure of DNA is made up of a twisting double helix with a sugar phosphate backbone.

5 Nucleotides
Within DNA there is one of four nucleotides, also known as bases. These structural building blocks of DNA are effectively he blueprints of an organism.

6 Coding
Nucleotides form specific pairs – adenine with thymine and cytosine with guanine. The arrangements in nucleotide sequences code for the production of certain proteins.

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some information is left behind or replaced, and a mutation occurs.

The effects of a mutation are wide-ranging. Tiny-point mutations, which occur at a single nucleotide base pair, occur trillions of times among the trillions of cells that make up an organism's body. The majority of these will be silent mutations that have no notable effect on the organism. However, there are occasions when these mutations can have implications for the physical appearance of an organism and how it behaves, or cause a myriad of health issues. As an example, polymelia is an uncommon condition caused by a genetic mutation that leads to the development of additional limbs. The condition is rarely seen in humans but is occasionally reported in domestic animals such as chickens and sheep.

Did you know?
On average, parents pass 60 new mutations to their children

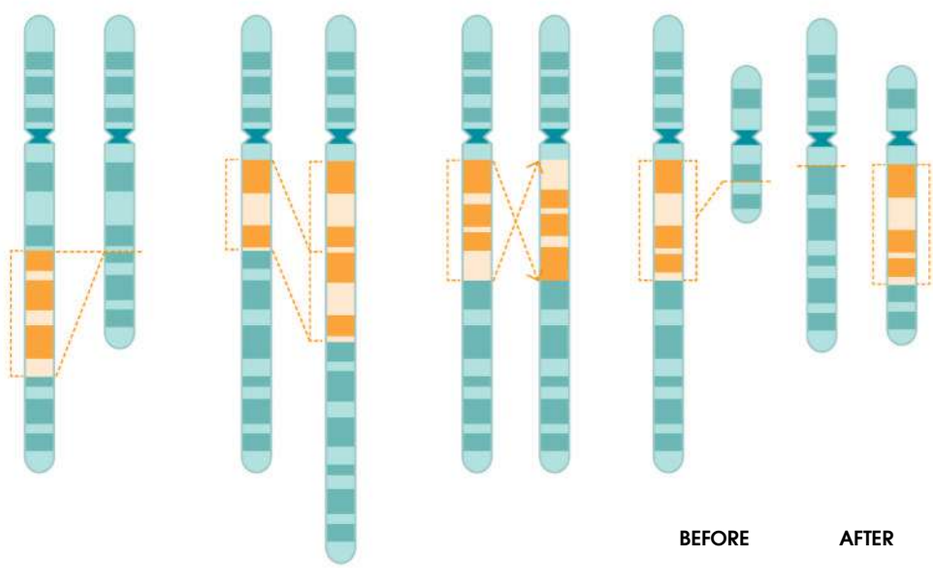
As to why mutations occur, scientists still don't have a complete picture. There isn't much scientific rhyme or reason when it comes to spontaneous mutations. Sometimes, during the process of cell division, errors are made in the replication of DNA, which results in a mutation. There are also active agents in the world that can tip the scales of genetic probability and cause a mutation. Active agents that cause a mutation are called mutagens and are either chemical or radioactive. Chemical mutagens are toxins that can alter DNA and lead to a whole host of health issues and congenital abnormalities. For example, the inhalation of asbestos can cause mutations that lead to the development of lung cancer.

One of the most striking physical mutations seen in the animal kingdom is known as bicephaly, or axial bifurcation, whereby an organism develops a two-headed but otherwise normal body. The most commonly reported organisms to experience this rare condition are reptiles, typically snakes. However, the condition has been seen in species across the animal kingdom and even with some human examples. Scientists aren't completely sure why the developing embryo doesn't completely split and instead continues to grow. Possible explanations for cases in reptiles in particular are fluctuations in external temperature during incubation, environmental pollution or exposure to chemical mutagens.

Ionising radiation can be an extremely damaging external mutagen. The exposure of

People in Tibet have evolved to live thousands of metres above sea level

Types of mutations

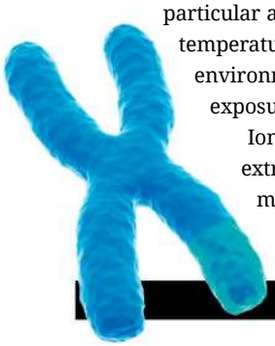


1 Deletion
This type of mutation occurs when one or more nucleotides from a portion of a DNA strand are lost. Deletion can lead to many genetic diseases, such as cystic fibrosis.

2 Duplication
This form of genetic mutation involves copying a DNA segment and repeating the same segment again before moving onto the next new segment.

3 Insertion
Rather than losing or repeating segments, this involves new nucleotide base pairs being added into a sequence. This type of mutation interprets the creation of vital proteins and leads to different birth defects.

4 Substitution
When one nucleotide is incorrectly swapped out for a different one. This replacement has an effect on the production of a protein, such as disrupting and altering its function or rendering it useless.



living tissue to high or prolonged levels of radiation – such as X-rays and ultraviolet light (UV) – can break down sequences in DNA, damage the structure of cells and lead to their mutation. The result of mutations caused by radiation is typically the development of cancers and growth of tumours, along with some physical abnormalities – just as it was in the wake of the tragic Fukushima Daiichi Nuclear Power Plant accident. In 2011, scientists discovered that the larvae of pale grass blue butterflies (Zizeeria maha), which were exposed to the radioactive fallout of the explosion, developed much smaller wings and irregular eyes compared to unexposed ones. These butterflies showed a mutation rate double that of butterflies found before the incident.

Often referred to as the 'raw materials' for evolution, genetic mutations are the fundamental building blocks for life on Earth.

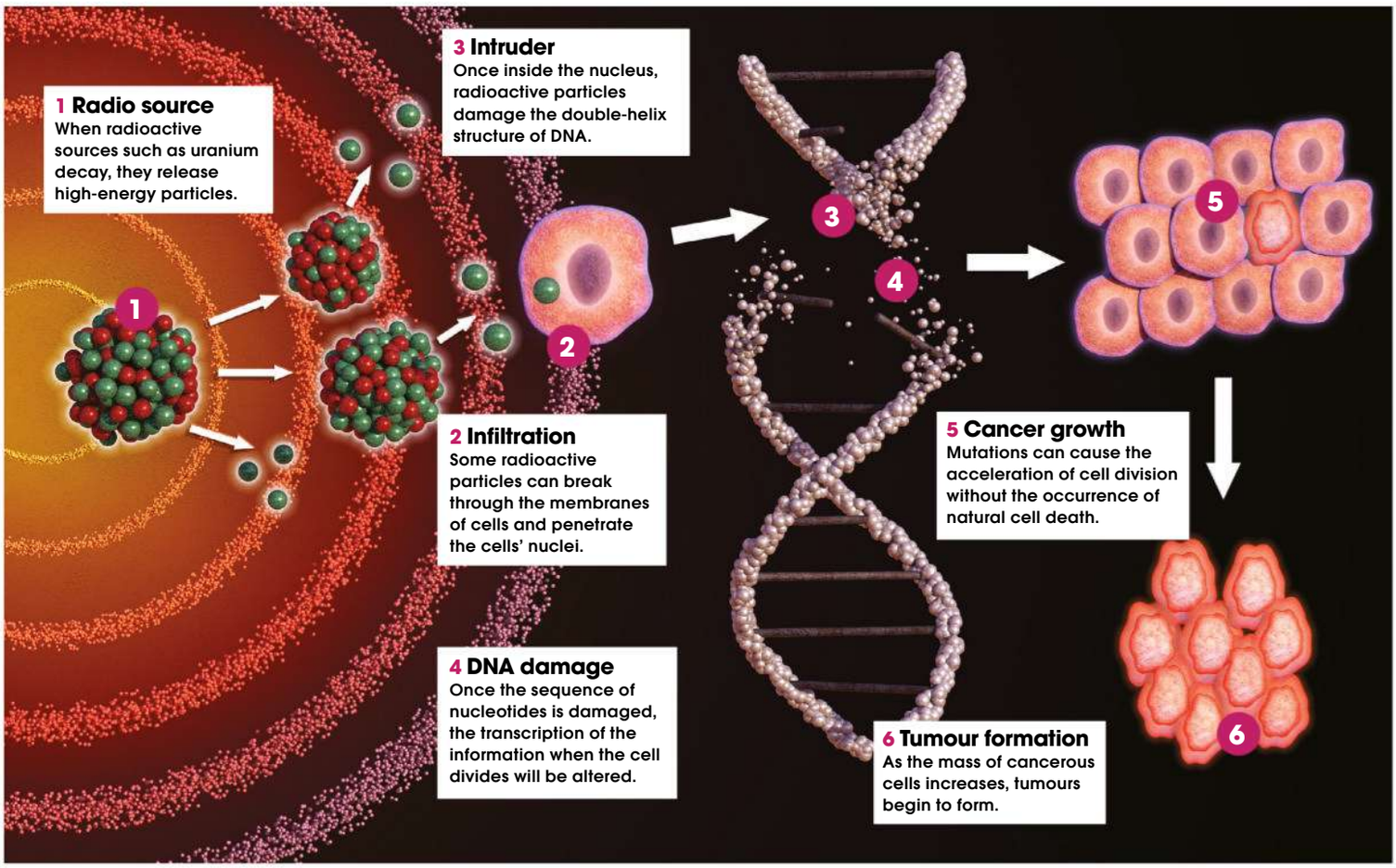
Mutant fruit

If you've ever bitten into an apple or cut into a tomato and found that the seeds inside have already begun to germinate, you've discovered a mutant fruit. The phenomenon of 'live birth' in some plants is called vivipary. This is where the seeds of plants start to germinate before they have matured and separated from the parent plant. While still nestled within the flesh of a tomato or sandwiched on an ear of corn, a hormone produced by the plant keeps the seeds from entering into the next stage of growth. However, if that hormone runs out, the seeds are free to germinate. In the case of vivipary plants, a genetic mutation inhibits the production of the germination-preventing hormone and tiny shoots prematurely emerge from the fruit.

The seeds of a tomato germinating while still in the fruit, a process known as vivipary

Radioactive mutation

How exposure to radiation can trigger genetic mutations



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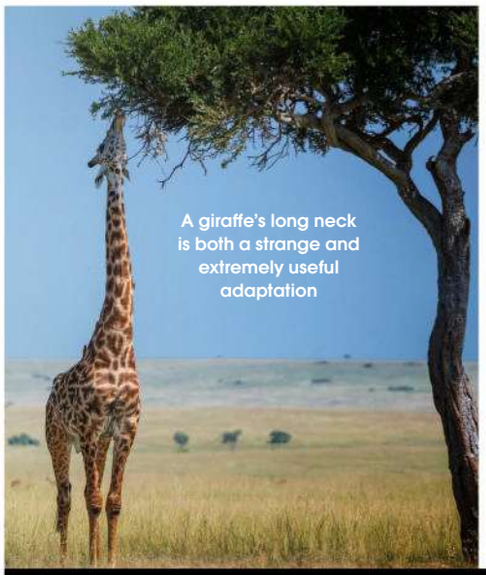
Albinism is a genetic condition where an organism doesn't produce melanin for colouring skin, hair and eyes

The father of evolution, Charles Darwin, penned the theory of natural selection in the mid-1800s, offering explanations for life and the biological journey it had undertaken through time to become what we know today. The theory of natural selection proposes that only members of a species that can adapt to their environments will survive long enough to reproduce and continue their lineage. However, Darwin remained in the dark about the role genetics played in evolution. That knowledge came from Dutch botanist Hugo de Vries at the beginning of the 20th century.

Natural selection is driven by mutations in an organism's DNA that cause a beneficial physical or behavioural trait that ensures its survival. Those traits are then passed on to the next generation, and over time the species evolves. Members of the species that don't genetically mutate and adapt often die before they can pass their DNA on to their offspring.

Did you know?
Ribonucleic acid (RNA) genomes can also mutate

For an entire species to evolve, the development and mutation of DNA occur over thousands of years. For example, over millennia, the DNA of some giraffes mutated to allow them to grow long necks and tall legs to reach parts of trees that other shorter giraffes and herbivores struggled to get to. Their long necks gave them an advantage and increased their chance of survival, although natural selection and mutation-driven evolution aren't a thing of the past. There are many examples of modern-day mutants, showing scientists the next potential stages in their evolution, including humans.



A giraffe's long neck is both a strange and extremely useful adaptation

Two-headed snakes and poison-protected mice are far from being alone in their mutations. To find one of the most advanced mutants on Earth, you need only look in the mirror. Considering the fact that genetic mutations are the raw materials of evolution, we as humans have undergone countless changes in our genetic makeup over the past 10,000 years to become the apex predators and technological innovators that we are today. Over millennia, both small and large mutations to the human genome have propelled our evolution and created the modern human, from the

MRSA
Staphylococcus aureus

As single-celled organisms, each time bacteria create a copy of themselves through cellular division, they run the risk of mutation. In 20 minutes or less, bacteria can double their population. When a mutation occurs, it quickly becomes the norm, such as in methicillin-resistant Staphylococcus aureus (MRSA): mutations have given it the ability to resist the effects of antibiotics.

MODERN-DAY MUTANTS

Mutations have allowed these species to adapt and survive

European house mouse

Mus musculus

Warfarin is a blood thinner used in pest control. The poison works by reducing vitamin K production, which helps the body form blood clots – an important process that prevents excess bleeding. A mutation in a gene called VKORC1 allows certain mice to produce more vitamin K and combat the blood-thinning ability of warfarin.

Green anole

Anolis carolinensis

In only 20 generations, green anole lizards have rapidly evolved to best a group of invasive brown anoles in the US. Within the span of 15 years, these tree-dwelling lizards have evolved larger toepads with more sticky scales that allow them to reach heights that their invasive competitors are unable to access.

Table coral

Acropora

Warming temperatures cause coral species to 'bleach', where they lose their vital algae and die. Research has shown that table corals have mutated to adapt to warmer waters. Heat-tolerant corals like these are more likely to survive in the face of a warmer climate and may evolve into the dominant type of coral in our oceans.

Peppered moth

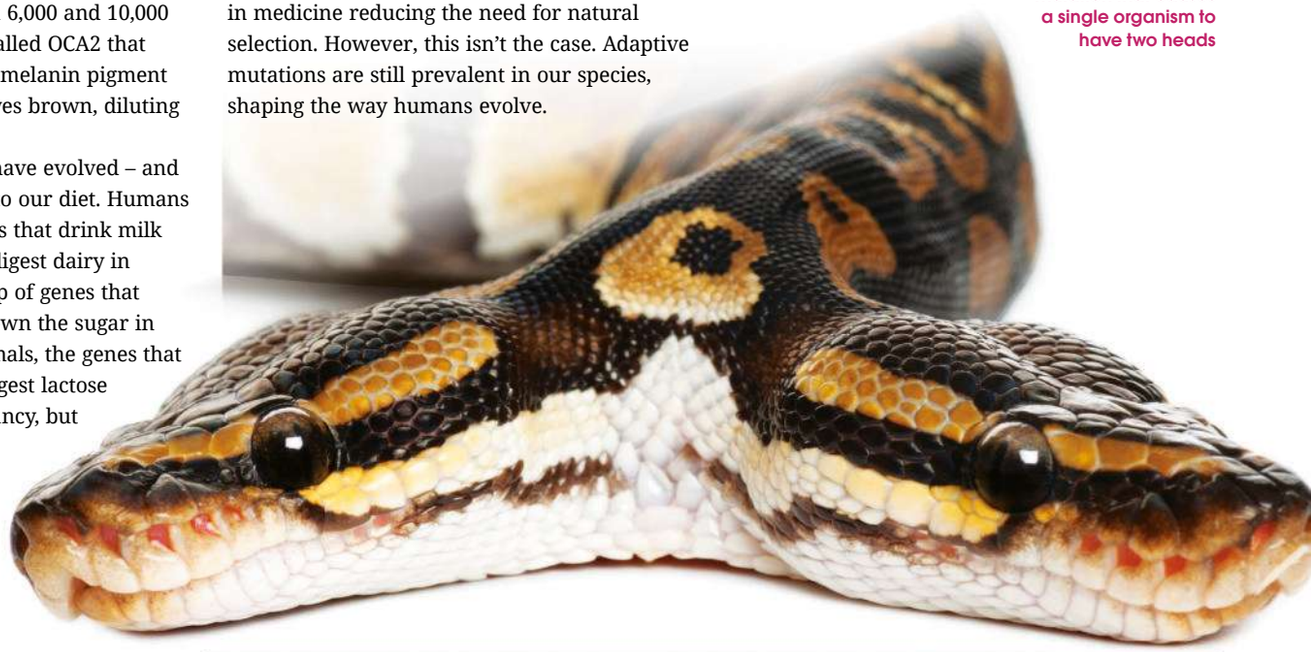
Biston betularia

These moths are naturally speckled white and black. During the rise of the Industrial Revolution, they were able to adapt and survive predation thanks to a mutation that emerged around 1819. It made these moths darker – almost completely black – allowing them to blend in on urban tree trunks that had been coated in soot.

© Getty

shedding of our body hair to the development of large brains. One example of a recent human mutation happened between 6,000 and 10,000 years ago, affecting a gene called OCA2 that halted the production of the melanin pigment in the iris that colours the eyes brown, diluting eyes to a shade of blue.

One of the ways humans have evolved – and continue to evolve – relates to our diet. Humans are one of the only mammals that drink milk after infancy. The ability to digest dairy in adulthood is down to a group of genes that allow our bodies to break down the sugar in milk, lactose. In other mammals, the genes that code for proteins that can digest lactose typically switch off after infancy, but a mutation in some humans stops that from happening. "We know there are four independent mutations that we see in various human populations, and they sit in the promotion of this gene," says Laurence Hurst, professor of evolutionary genetics at the University of Bath. "Rather than it being switched off, it gets switched back on again." Over the last 8,000 years, this has led to around 90 per cent of Northwestern Europeans having the ability to digest lactose. It's often thought that humans have jumped off the evolutionary train and have reached their final biological destination, likely due to advancements in medicine reducing the need for natural selection. However, this isn't the case. Adaptive mutations are still prevalent in our species, shaping the way humans evolve.



A royal python with bicephaly, a genetic mutation that causes a single organism to have two heads

Polymelia is a mutation that causes an organism to grow extra limbs, like this four-legged chicken

The ever-evolving human

How some members of our species from around the world are evolving

1 Altitude tolerance

In less than 3,000 years, some Tibetans and Han Chinese people have evolved to live at altitudes most people could not – at altitudes of 4,000 metres where the oxygen levels are around 40 per cent lower than at sea level, Tibetan villagers have been thriving in the thin air. Researchers have identified 30 genetic mutations within those people who live at these impressive altitudes, half of which are related to the way the human body uses oxygen and helps the individual manage haemoglobin concentrations.

2 Deep divers

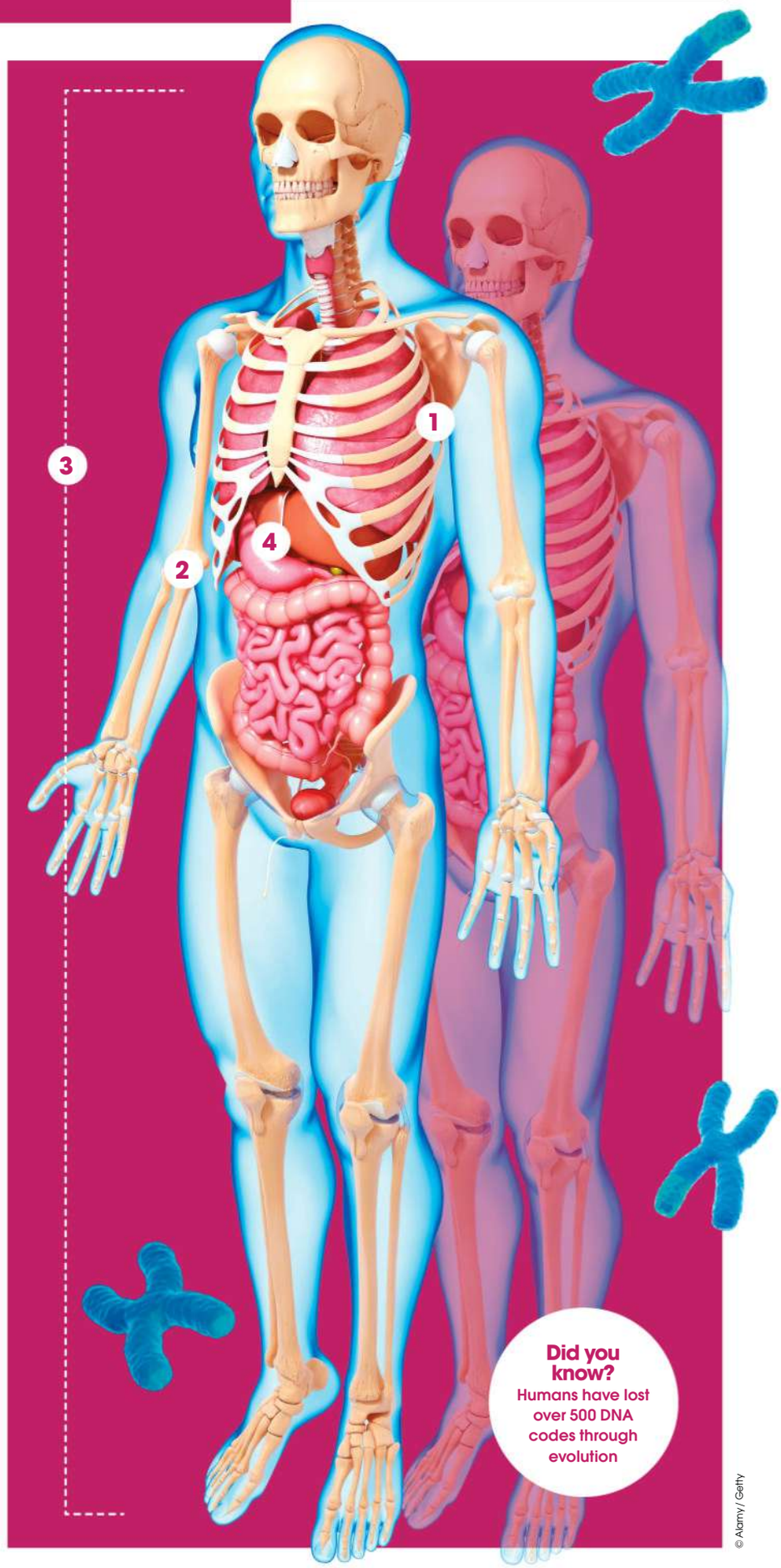
The deep-sea-diving Bajau people of Southeast Asia have shown a remarkable example of human evolution by building the biological equivalent of a scuba tank. The human spleen is typically used to filter blood as part of the body's immune system. Through genetic mutations, the people of Bajau have evolved a larger spleen than most, around 50 per cent bigger on average. A large spleen can act as a reservoir of oxygenated blood while diving, allowing the Bajau people to deep dive up to 70 metres below the surface.

3 Getting taller

In the mid-18th century, the average Dutch soldier was recorded to be 165 centimetres tall. However, the modern-day Dutchman is a towering 182.5 centimetres tall on average. Over the same period, the average American has grown by only six centimetres. It's thought that the 20-centimetre increase is down to natural selection – a preference for tall men among Dutch women.

4 Vegetarian nutrition

Scientists found that 70 per cent of vegetarians in Pune, India, that they surveyed have a genetic mutation in the FADS2 gene that allows them to produce essential omega-3 and other fatty acids from a non-meat diet. Fatty acids such as omega-3 are abundant in fish and red meat, but sparse in vegetables. The FADS2 mutation is thought to help vegetarians effectively process these fatty acids from alternative sources.



Did you know?
Humans have lost over 500 DNA codes through evolution

© Alamy/ Getty

Cats vs dogs

How the psychology and biology of the world's most popular pets compare

EVOLUTION

Humankind's canine companions and feline friends belong to an order of animals called Carnivora. They are the descendants of the first mammals of the late Paleocene epoch that hungered for the flesh of other animals. Between 65 and 35 million years ago, an order of weasel-like animals called Miacis skulked through the trees of ancient woodlands across Eurasia and North America. These furry mammals were arboreal creatures, meaning they spent their time hunting among the lush vegetation of the Paleocene forest. Although Miacis was one of the earliest carnivorous mammals on Earth, it was by no means the most ferocious.

Following the extinction of the dinosaurs around 66 million years ago, two mammalian hunters rose to the top of the food chain: wolf-like predators called creodonts and the hoof-footed ancestors of marine mammals, called mesonychids. Both of these apex predators met their extinction due to an overlap of resources and competition with other carnivores. Miacis, on the other hand, began a lineage of mammals that resulted in the evolution of prolific predators in the modern world, such as lions, tigers and bears. Around 43 million years ago, the carnivorous descendant of Miacis diverged into two distinct paths – the 'dog-like' Caniformia and the 'cat-like' Feliformia. Over millions of years, they evolved into the feline and canine species seen today, including the domestic cat and dog.

The evolutionary road to becoming the cats and dogs we know today didn't occur through typical means. Unlike the pressures of natural selection that their wild cousins have endured for millennia, cats and dogs owe their current form to their interactions with humans. Dogs were the first to find human companionship around 23,000 years ago. Some of the most recent genetic research suggests that prehistoric grey wolves and humankind evolved in tandem in Siberia in the late Pleistocene. Over thousands of years of benefiting from hanging around one another for food and

"Following the extinction of the dinosaurs around 66 million years ago, two mammalian hunters rose to the top of the food chain"

Social cues evolve, too, and cats have developed a greeting ritual where they touch noses

© Getty

safety, prehistoric people likely bred the tamest of wolves into domesticated allies.

Cats, on the other hand, befriended people around 10,000 years ago. It's long been believed that ancient Egyptians were the first to tame wild cats and keep them as pets. Depicted in hieroglyphs as magical creatures and mummified with their human companions, cats played a significant role in the lives of Egyptians from 3,600 years ago. However, this is far from the first time cats and humans cohabited. Researchers have examined the DNA of the common household cat's wildcat ancestor (Felis silvestri) and traced it back to the first human settlements in the Middle East, known as the Fertile Crescent and also referred to as the cradle of civilisation. It remains unclear exactly why cats found their way into human lives, but some DNA evidence suggests they may have self-domesticated. As hunters of pesky rodents, ancient farmers likely kept cats around as a form of pest-control.

Most dog breeds we recognise today developed in the last 150 years. However, the oldest domesticated dog breed is the Saluki. Mummified remains of these slender pooches that have been found in Egypt have been

Prehistoric rivals

Cats and dogs have long been rivals. In 2015, researchers from the University of Gothenburg in Sweden, São Paulo in Brazil and Lausanne in Switzerland analysed more than 2,000 fossils and discovered that prehistoric cats contributed to the extinction of up to 40 different species of the canine family. Around 22 million years ago, when dog diversity was at its peak in North America, researchers discovered typical causes of extinction, such as climate change, that were as deadly to prehistoric dogs as competition from resourceful felines. The research concluded that prehistoric felids were likely more efficient predators and out-hunted many prehistoric dog species for food.

Fossils reveal that competition with cats drove many prehistoric canines to extinction

Common ancestor

Miacids were the prehistoric ancestors of both cats and dogs

1 Claws
Miacids had five-clawed paws to scale trees and grapple with prey.

2 Carnivores
These prehistoric predators likely hunted and fed on reptiles, birds, insects and other small mammals.

3 Small predators
Miacids had a diverse range of body sizes, from one to seven kilograms.

4 Adapted feet
As arboreal creatures, their hind feet were capable of turning backwards to grip trees.

5 Prehensile tail
Like many tree-dwelling animals, miacids had tails that could grasp onto branches.

Family tree

Discover the genetic relatives of cats and dogs

- **Carnivora**
  - **Feliformia** — The suborder that encompasses the world's species of 'cat-like' animals.
    - **Nandiniidae** — Only one animal belongs to this feline family: the African palm civet.
    - **Stenoplesictidae**
    - **Percrocutidae**
    - **Feloidea** — A superfamily that comprises smaller Feliformia families, including civets and the domestic cat.
      - **Prionodontidae**
      - **Barbourofelidae**
      - **Felidae** — The family of animals that includes the world's big cat species, bobcats and domestic cats.
    - **Viverridae** — Small feline-like families that include species such as the African civet and binturong.
      - **Viverridae**
      - **Herpestoidea**
        - **Hyaenidae**
        - **Herpestidae**
        - **Eupleridae**
  - **Caniformia** — The suborder that encompasses the world's species of 'dog-like' animals.
    - **Amphicyonidae**
    - **Canidae** — Along with dogs, this family of 34 canids includes coyotes, foxes and wolves.
    - **Arctoidea**
      - **Hemicyoninae**
      - **Ursidae** — This family consists of the world's eight species of bear, including the brown bear, polar bear and giant panda.
      - **Pinnipedia** — This suborder of animals comprises the world's seal and walrus families, with a total of 34 different species.
        - **Enaliarctidae**
        - **Phocidae**
        - **Otariidae**
        - **Odobenidae**
      - **Musteloidea** — A suborder of small mammal families of 88 different species including skunks, raccoons and otters.
        - **Ailuridae**
        - **Mephitidae**
        - **Procyonidae**
        - **Mustelidae**

"Most of the dog breeds we recognise today developed in the last 150 years"

© Alamy / Getty / Michele Silvestro / Science Photo Library

5 Signs your dog loves you

1 Tail wagging
The movement of a dog's tail is a display of their current emotion. A wagging tail – sometimes in a circular motion – and a smiling face are a good sign your pup is pleased to see you.

2 Licking
Similar to how their wolf ancestors licked their mothers for attention and food, if a dog likes you, a lick on the hand can mean they want your attention.

3 Cuddling
When a dog chooses to jump up onto the sofa for a quick cuddle, it's a pretty good indication that they enjoy your company.

4 Following
Over time, dogs come to associate their owner with things such as food and play, which release a happy hormone called oxytocin. They follow their owner around in case there's another hit of oxytocin on the way.

5 Eye contact
Normally, dogs aren't that forthcoming with eye contact. However, when a dog chooses to look at you with soft, relaxed eyes, they're attempting to form a bond with you.

Both are expert nappers, but cats spend a little bit longer sleeping than dogs

dated to 329 BCE. There have also been carvings found in Iraq that resemble the Saluki, dating back to 7,000 BCE. At present, there are around 340 unique dog breeds and 42 breeds of cat. Scientists suggest that extended periods of selective breeding for both functional and aesthetic qualities, such as herding and hunting skills, as well as coat colour and size, have led to the creation of modern-day canines. Cats have been less selectively bred for their abilities and remain relatively similar in appearance to each other when compared to dog breeds. Despite the large range of dog breeds, their DNA is only one per cent different from other breeds' on average, whereas individual cat DNA differs by up to four per cent.

Along with their obvious physical differences, the two don't have very much in common, except for both being great companions. One of the main differences between cats and dogs is their behaviour. As keen sleepers, both cats and dogs spend a considerable amount of time asleep. On average, felines spend up to 16 hours a day taking a cat nap, whereas dogs are a little more active, needing up to 14 hours of sleep. Cats are often thought of as nocturnal animals, when in fact they are crepuscular, which means that they are most active during dawn and dusk. It's thought this preference for low light relates to their behavioural adaptation to pounce on their prey during twilight. By contrast, dogs spend up to 80 per cent of their time asleep during the night, known as diurnal sleeping.

The pair also have different dietary requirements. Cats need a higher source of meat protein and vitamin A than that found in a dog's diet. This is mostly because cats are unable to produce important amino acids, such as taurine, and have to source it from their food. Dogs can produce these proteins in their body and therefore have a broader diet.

'Fighting like cats and dogs' is a phrase that's often bandied around to describe conflict, but the idea that these pets are mortal enemies isn't exactly true. When a dog sees smaller furry animals running quickly away from them, their built-in predatory instinct kicks into gear. In the same way, it may respond to seeing a rat or rabbit, its instinctual response is to chase it. Cats typically respond defensively and are likely to take a swipe at an advancing dog. Similarly, the difference in their greeting styles can cause some tension. While dogs like to engage in a bit of butt-sniffing to introduce themselves, cats greet each other by touching their noses together. This miscommunication can lead the pair to butt heads – and tails – from time to time. However, through periods of socialisation, especially effective when kittens and puppies coexist, the pair can form furry friendships that last a lifetime.

"Felines spend up to 16 hours a day taking a cat nap, whereas dogs are a little more active, needing up to 14 hours of sleep"

A cat flea

A dog flea

Unique fleas

Along with their many physical and behavioural differences, cats and dogs also have their very own species of fleas: cat fleas (*Ctenocephalides felis*) and dog fleas (*Ctenocephalides canis*). At first glance, you might be mistaken in thinking all parasites leaping through your pet's fur are the same. The anatomical differences between these fleas are small, with dog fleas having a more rounded head and more hair-like structures called setae. Cat fleas are much more common than dog fleas. Although they are named after their feline hosts, cat fleas can be found on a whole host of species, whereas dog fleas are limited to just their canine feeding grounds.

Dog diversity

On the surface, dog breeds are wildly different from their feline counterparts. For example, the largest dog breeds in the world are 40 times bigger than the smallest dog breeds. But when you dig deeper into the DNA of our canine and feline friends, there are some interesting differences. Despite all the colours, shapes and sizes of floppy ears, long tails and fluffy coats, there's only a tiny percentage difference in the DNA between the world's different dog breeds. Meanwhile, cats average a slightly larger average DNA difference among fewer cat breeds. Of the roughly 19,000 canine genes, variations in only 14 of them give rise to the many differences in appearance.

Along with a phenomenon called domestication syndrome, whereby the physical appearance of an animal changes in response to generational tameness, thousands of years of selective breeding have altered the combinations in dog DNA to create the hundreds of breeds we have today. Cats, on the other hand, have not experienced selective breeding on the same level as dogs, though there is still time. Over the next hundred years or so, floppy-eared felines, curly-haired cats and tall tabbies might become the norm.

Despite looking wildly different, there isn't much genetic difference between dog breeds

Meet the pet geneticist

Kennel Club genetics research manager Dr Joanna Ilska sheds some light on how dog breeds are defined

How is a new dog breed defined?

A breed is considered to be a population of dogs with clearly observable and heritable characteristics that have been attained by selective breeding over a period of time. The breed is documented through the pedigrees, tracking the ancestry of the individual dogs.

There are no specific genetic criteria which would determine whether a population can be described as a breed. From the point of view of genetics, a breed is simply a population of individuals, with all the genetic variants they possess. The genetic variants in a population evolve over time, as some variants will be lost through selection or random chance, while new variants will be added through novel mutations. As such, the breed population we see today is very likely to be genetically different to the same breed population many generations ago. Further, breed populations which are separated, geographically or through function, may also start to diverge genetically while still retaining the same observable breed characteristics.

Why are there so many more distinct dog breeds?

Dogs are highly social, with very well-developed instincts to cooperate with their pack members. This formed a fertile ground for selection for a whole range of different traits, where natural instincts inherited by dogs from their wild ancestors were shaped and moulded to specific functions benefiting humans in the process of domestication. Over time, these functions became more and more specialised, leading to a range of behavioural and physical attributes unique to dogs performing these functions – from highly athletic and resistant to cold Siberian Huskies pulling sleds in the Arctic to short-legged Dachshunds hunting badgers in their burrows.

Domestication of cats has been far more limited – they still retain many of their 'wild' characteristics and are fully capable of surviving in the wild. Cats are less social than dogs or wolves and don't have the same propensity for cooperation. As such, early humans coexisted with cats benefiting from their natural desire to hunt vermin. While formal breeds – with breed standards and pedigrees in both dogs and cats – are a fairly recent phenomenon, dog breeds have been developed from already-existing populations specialising in specific roles. On the other hand, with few exceptions, cat breeds have been developed primarily for aesthetic value.

How long can it take for a new dog breed to emerge?

Historically, most breeds were created over long periods of time, with dogs gradually becoming more uniform as the best performing dogs were selected to produce subsequent generations. Nowadays, the knowledge of genetics allows for much faster progress, with a much more precise selection of the best individuals, as well as much easier access to breeding dogs from across the world. However, the exact time needed to create a new breed will vary depending on a number of factors.

Firstly, the speed with which uniformity can be achieved will depend on the number and type of traits that will differentiate this new breed. The fewer the traits and the simpler their genetic architecture – how many genes are involved and the mode of inheritance – the easier it will be to develop a uniform population. Secondly, the more diverse the dogs used as a founding stock for the new breed are, the more generations it will take before their descendants are uniform. Thirdly, there needs to be a balance between selection intensity and inbreeding. High selection intensity increases the speed with which uniformity can be achieved, but it also carries with it higher levels of inbreeding, which may reduce the health and fitness of the breed.

The most popular cat breed in the US is the Ragdoll

© Alamy / Getty / The Kennel Club

Comparing companions

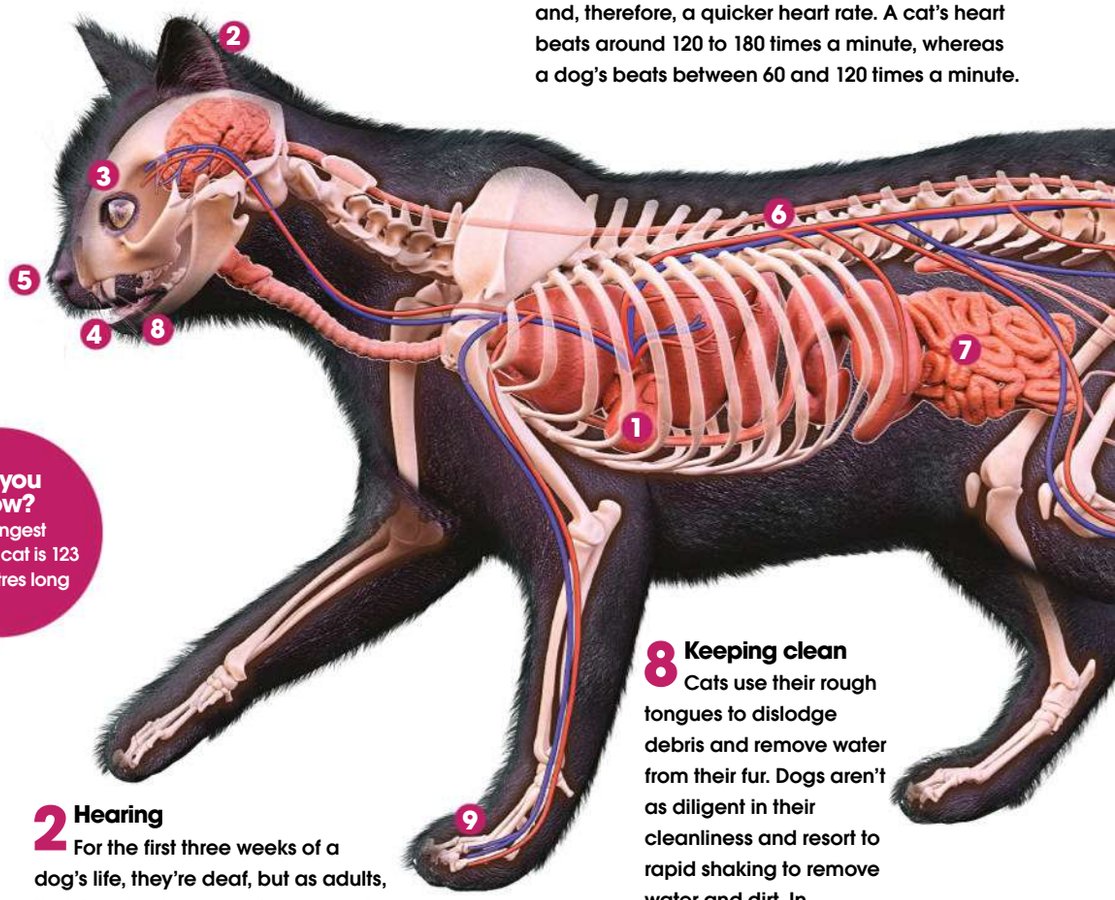
The physical similarities and differences between cats and dogs

As mammals, cats and dogs share a lot of similarities. They're both warm-blooded, air-breathing, fur-covered creatures with almost the same organs. However, there are some differences in their physiology. For example, their brains are set up slightly differently from one another. Typically, a dog has a bigger brain than a cat, and a larger portion of its mass is dedicated to the cerebral cortex. This part of the brain is responsible for receiving and processing sensory information – the smells, sights and sounds a dog encounters – along with decision-making and social interaction.

Cats have developed a brain that favours areas such as the hippocampus that are responsible for memory development, navigation and movement. Dogs have twice the number of neuron cells that transmit information around the brain than cats. A group of researchers from institutions around the world analysed the brains of cats and dogs, along with many other carnivores, and found that the cerebral cortex of a dog had 530 million neurons, whereas cats had 250 million. It's not just domesticated cats that are beaten out, but African lions and brown bears, too. However, this doesn't necessarily mean that dogs are smarter than cats. Countless studies have been devoted to assessing the cognitive abilities of our furry companions, but no consensus has been made about their overall intelligence.

Did you know?
15 minutes of petting a dog can lower blood pressure by ten per cent

Did you know?
The longest domestic cat is 123 centimetres long



1 Heartbeat
Due to their sizes, cats and dogs have very differently sized hearts, but they're typically up to 1.25 per cent of their total body weight. However, smaller animals tend to have faster metabolisms and, therefore, a quicker heart rate. A cat's heart beats around 120 to 180 times a minute, whereas a dog's beats between 60 and 120 times a minute.

2 Hearing
For the first three weeks of a dog's life, they're deaf, but as adults, their hearing is around four times stronger than a human's. Cats can hear much higher sound pitches than dogs – around a single octave.

5 Smell
Dogs are proficient sniffers, with a sense of smell that's 100,000 times better than a human's. Dogs have up to 300 million smell sensors in their noses that can sniff out smells 12 metres underground. Cats aren't too shabby either, with 200 million odour sensors in their noses, giving them a sense of smell that's 14 times better than ours.

8 Keeping clean
Cats use their rough tongues to dislodge debris and remove water from their fur. Dogs aren't as diligent in their cleanliness and resort to rapid shaking to remove water and dirt. In seconds, dogs are able to shake off 70 per cent of the water in their fur.

9 Claws and paws
A swipe from a cat and a dog is a very different experience. Cats are armed with razor-sharp retractable claws designed for scaling trees, whereas dogs have evolved duller nails which grind down as they walk.

6 Spines
As agile predators that descend from arboreal ancestors, cats have evolved a flexible and rotatable spine, allowing them to contour their bodies and squeeze through tight spaces. The discs between the bones of the spine have an increased elasticity when compared to the more rigid and sturdy structure of a dog's spine.

3 Eyesight
Looking ahead, dogs have a field of vision that spans 240 degrees, whereas cats fall just short at 200 degrees. A cat's night vision is marginally better, although the two share the inability to witness the full spectrum of colours that humans do.

4 Teeth
Cats and dogs have sharp premolars called carnassials, designed to slice and grind meat. Cats are born with 26 deciduous teeth, which are replaced by 30 permanent teeth after the first 11 weeks of their life. Dogs start with 28 deciduous teeth before a full set of 42 teeth erupt at around six months old.

7 Digestion
The digestive systems of both cats and dogs are relatively similar. However, cats are strictly carnivores, whereas dogs are omnivorous. The high levels of fat and protein that make up the feline diet means the cat liver is adapted to functioning on low carbohydrate levels.

The Saluki is the oldest known modern-day dog breed, dating back to ancient Egypt

Kitty claws

How cats retract their claws

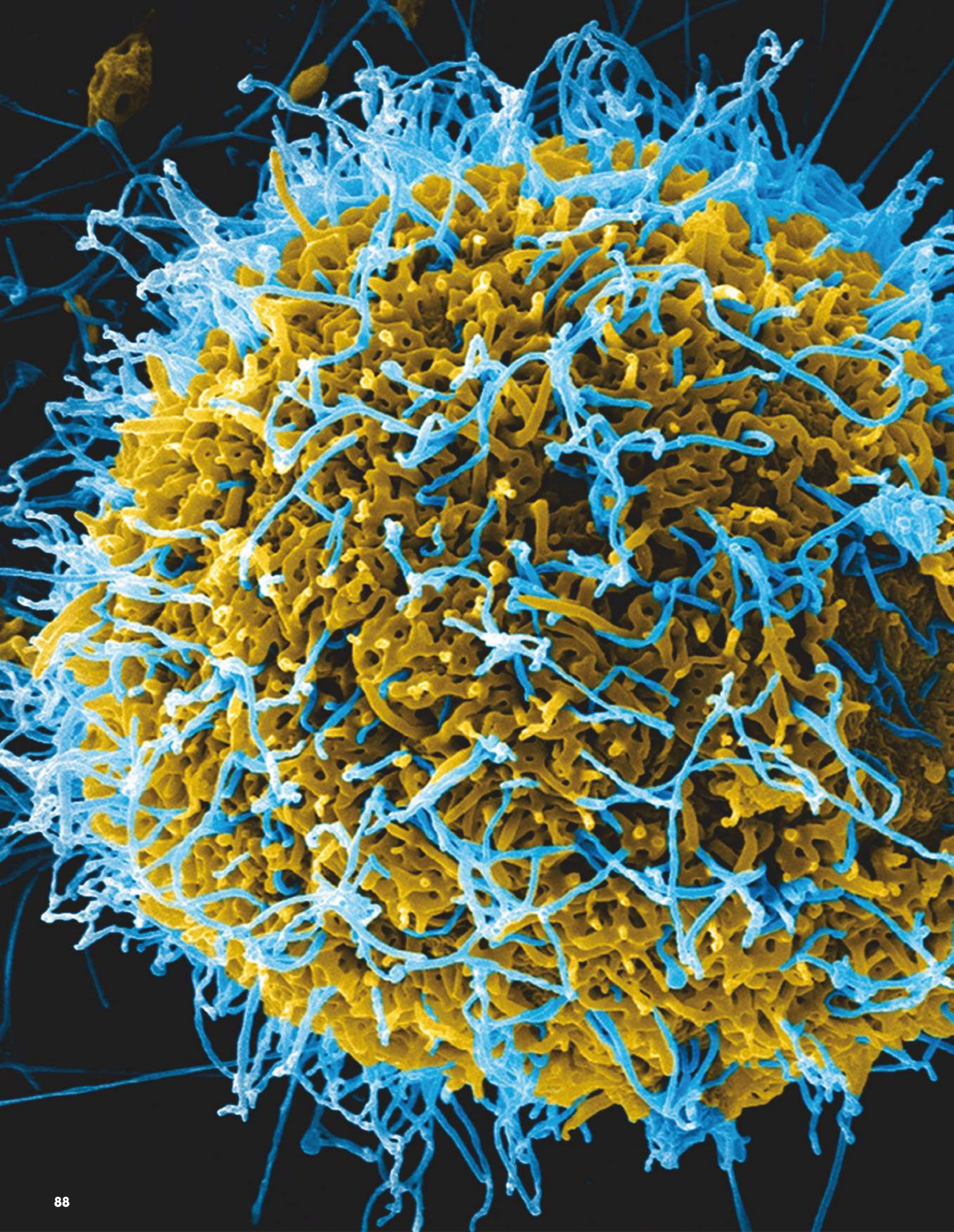
10 Claws
Cats extend their claws and drag them down hard surfaces to keep them razor sharp.

11 Elastic ligament
This muscle contracts to retract the cat's claws when signalled to by the brain, tucking the claws back into the paw.

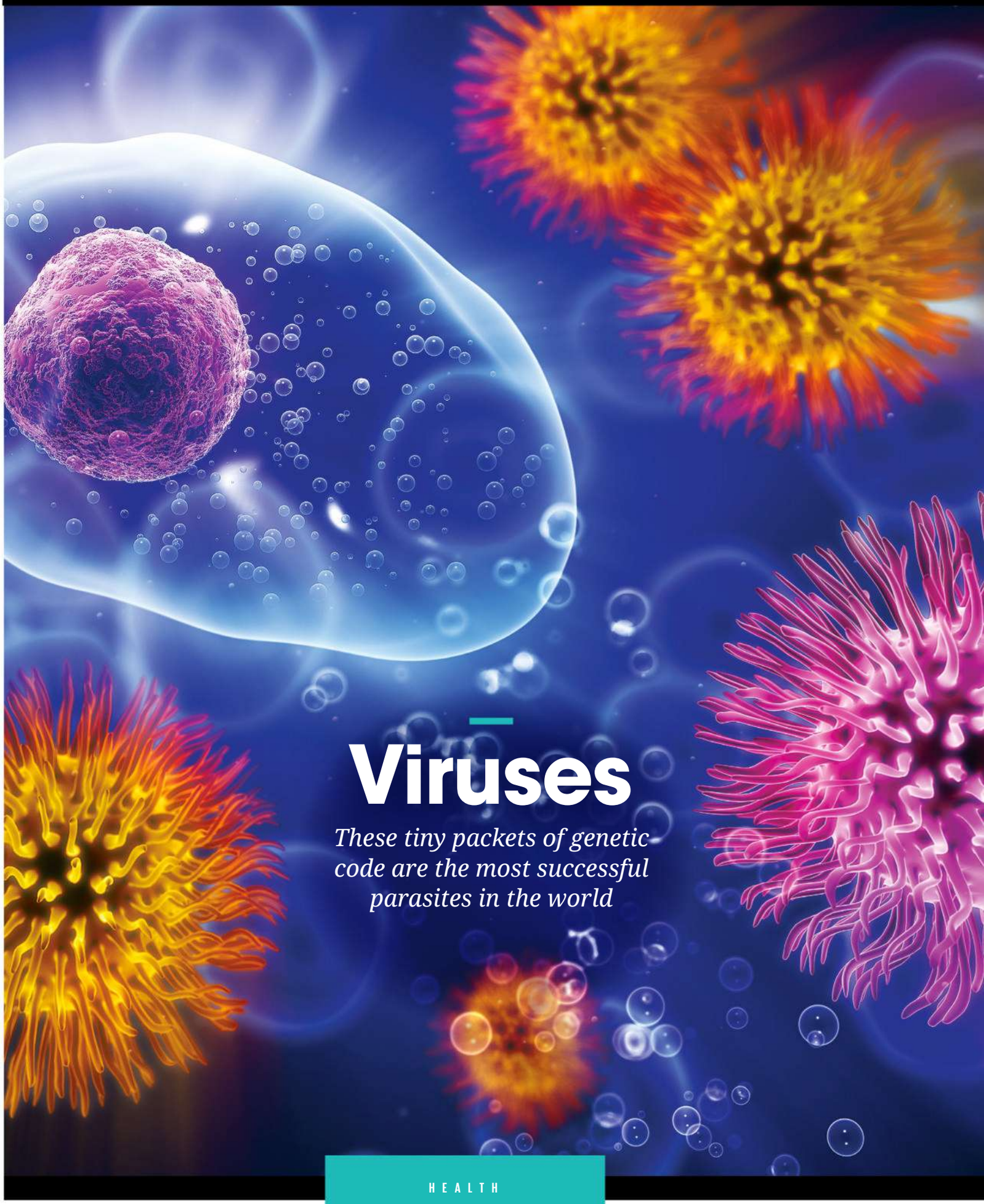
12 Digital flexor tendon
When tightened, the tendon attached to the bone in the foot pulls the bone back and extends the claw outwards.

13 Digital extensor tendon
As the opposite of the flexor tendon, this muscle contracts to draw the cat's bone back, bringing the claw with it.

© Getty / Illustrations by Nicholas Forder



Health



Viruses

These tiny packets of genetic code are the most successful parasites in the world

HEALTH

Viruses are the tiniest biological replicators on the planet, roughly 100 times smaller than bacteria. Made from a small strand of genetic code and covered with a tiny protein shell, they can't 'live' on their own. In fact, scientists aren't sure whether they're even alive at all.

The cells of living organisms have their own molecular production lines. They make temporary copies of their genes and pump them through molecular machines called ribosomes. These read the genetic code and use it as a template to assemble proteins. The simplest living organisms need between 150 and 300 genes to make all the proteins they need to survive, but viruses get by on as few as four. They simply hijack other cells and turn them into virus factories.

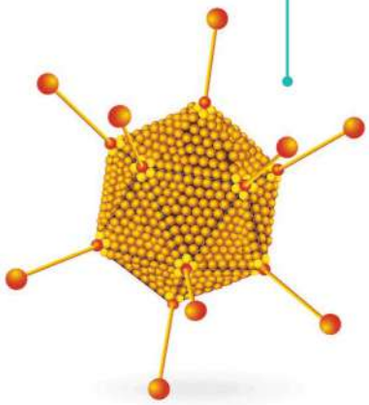
Viruses are clever; they make up for their genetic shortfall by borrowing from the cells they infect. They don't have their own ribosomes, so they feed their code into the machines of other organisms, taking over the production line. The infected cell stops making its own proteins and starts reading virus code and assembling virus proteins.

The core of a virus is its genetic code, which is stored in the same strings of biological letters used by living organisms. Some viruses have two strands of DNA like us, others get by with just one strand, and some carry their genes as RNA. This molecule is like DNA but with a different chemical letter, and it's used by living cells to make temporary copies of genes. Some viruses also carry the code to make an enzyme

All shapes and sizes

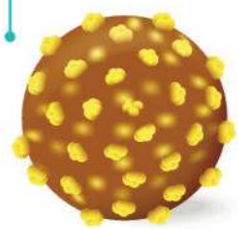
Viruses may be small and simple, but they're very effective

Virologists use protective equipment to study human viruses in the lab



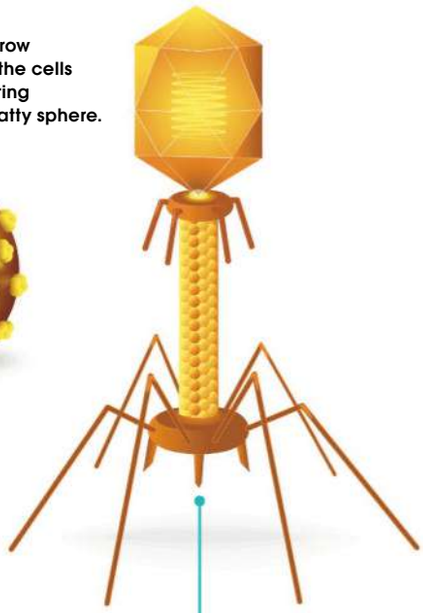
Polyhedral

The outside of these viruses is a regular 3D structure, most often a 20-sided ball.



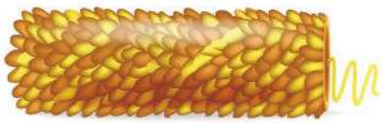
Spherical

These viruses borrow membrane from the cells they infect, covering themselves in a fatty sphere.



Complex

These viruses have irregular shapes and do not fit neatly into the other categories.



Helical

The genetic code of these viruses is covered in a twisted tube-shaped coat.

> "Viruses simply hijack other cells and turn them into virus factories"

Are viruses alive?

This is still a topic of debate among scientists. Viruses do not fit into our definitions of life, but they share some 'life-like' characteristics

ALIVE

"Viruses use the same molecular building blocks as other living organisms: RNA, DNA and protein"

"Viruses evolve and have made complex changes to their genetics to adapt to their unique environments"

"Lots of other parasitic organisms depend on others for survival and cannot exist on their own"

DEAD

"Viruses have a protective protein coat, but they do not have a membrane and are not cells"

"Viruses don't use any energy when they're floating between cells. They simply exist"

"Viruses cannot copy their own genetic code – they need living cells to do it for them"

called reverse transcriptase, which allows them to convert RNA into DNA inside a living cell.

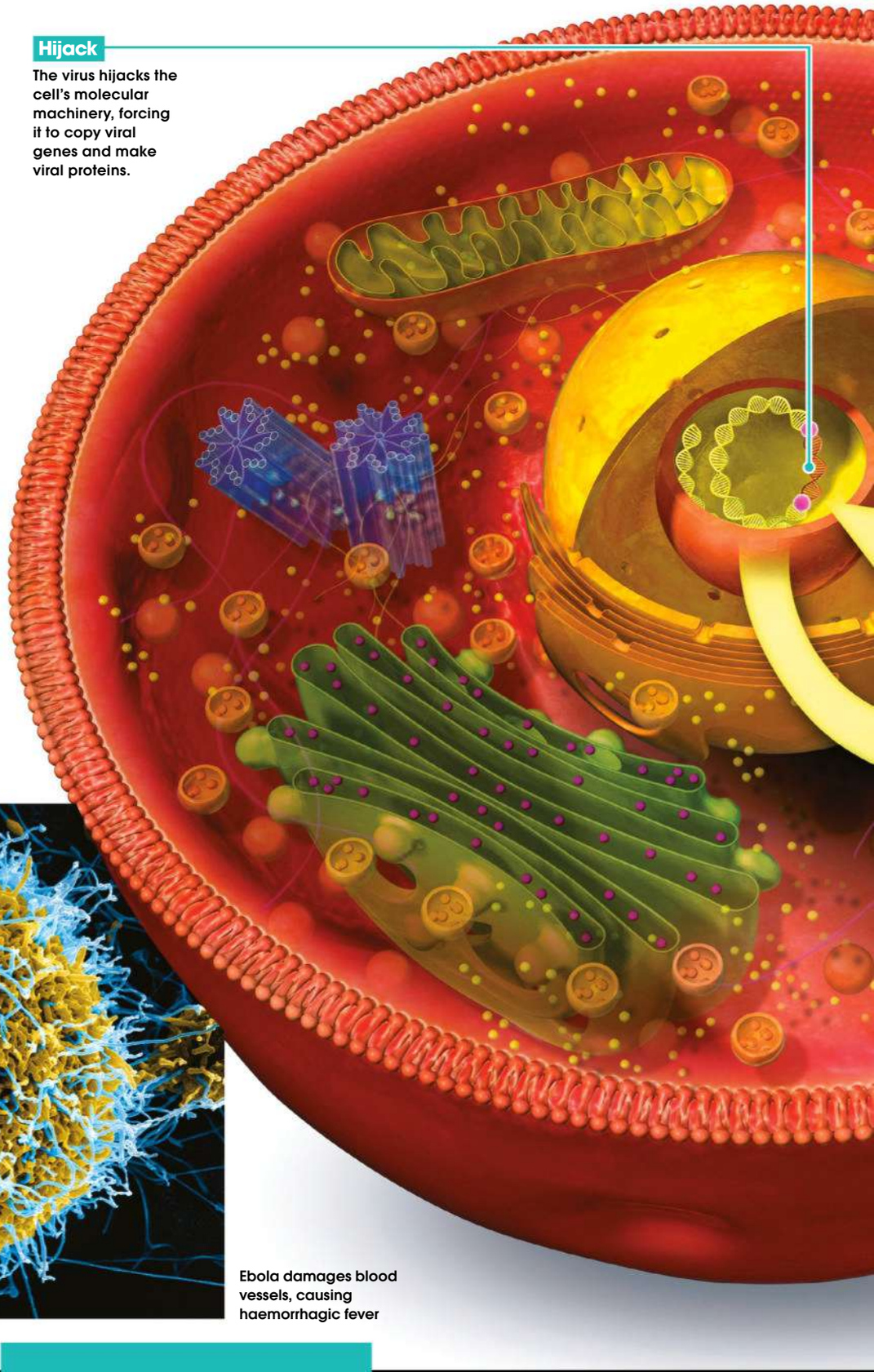
Genetic information is fragile, so to move from one cell to the next, viruses need a way to protect their code. Some of their most important genes provide the instructions to build proteins that make a protective coat called a capsid. The capsid proteins form repeating structures that lock together to make a 3D shape. This crystal-like patterning means that viruses only need a few genes to make a complete shield. Icosahedral capsids, for example, often contain small triangles made from just three proteins. These triangles slot together to make a 20-sided ball that covers the viral genome.

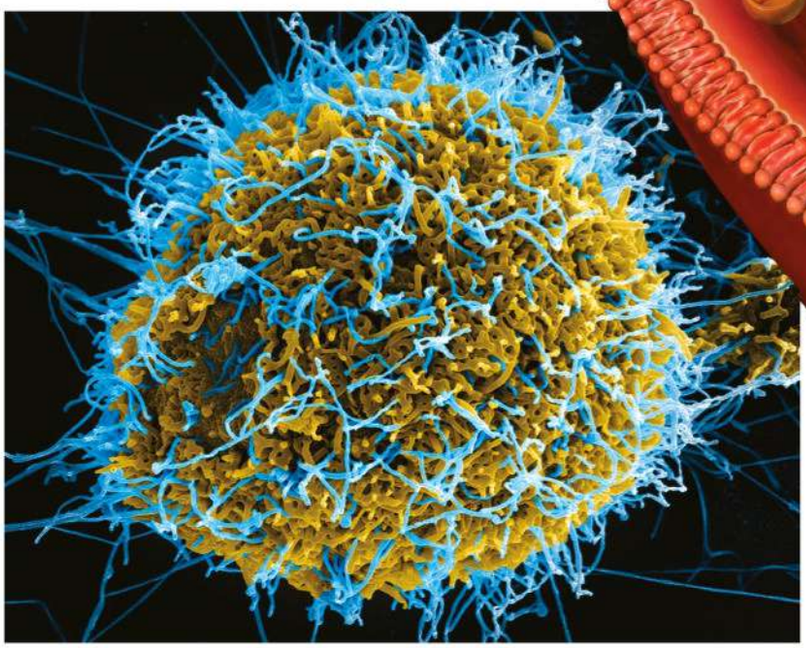
The infectious packages of capsid and genetic code can survive outside of cells, but they can't replicate on their own. Known as virions, these virus particles need to get back into cells to continue their lifecycle. They do this by attaching to molecules on the cell surface.

Proteins on the outside of the capsid interact with proteins on the outside of the cell. This attachment may change the shape of the virion itself, allowing the particle to fuse with the cell membrane. Alternatively, it might trick the cell into pulling the virus into a membrane-covered sphere known as an endosome. Once inside, enzymes carried by the virion – or from the cell itself – break down what's left of the capsid, releasing the genetic code into the cell. The viral genome then enters the cell's production line and quickly begins manufacturing three main types of protein.

Virus production

These pathogens turn cells into miniature virus factories





Ebola damages blood vessels, causing haemorrhagic fever

Entry
The virus particle fuses with the cell membrane, injecting its contents into the cell.

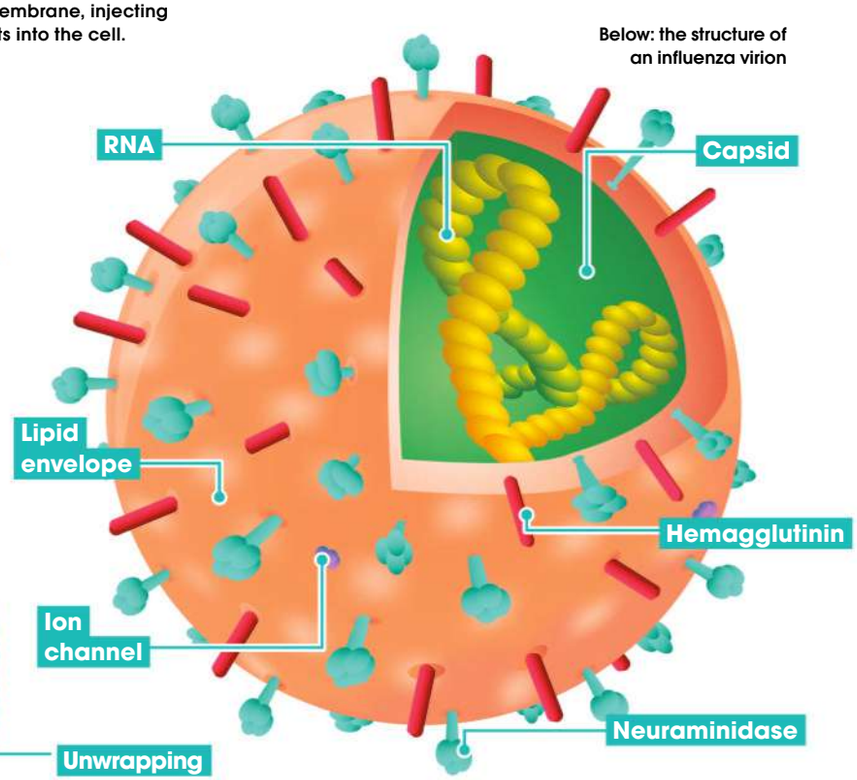
Unwrapping
The outside of the virus breaks apart, releasing the viral genetic code into the cell.

Construction
Viral proteins assemble into protective cages around copies of the viral genome.

Release
Virions leave via a process called 'budding', taking part of the cell membrane with them.

"Lytic viruses simply burst out, releasing all their virions in one huge pop"

Below: the structure of an influenza virion



The first are enzymes that enable the virus to construct more copies of its own genes. The second are proteins that interfere with the cell's normal manufacturing processes. The third type are the structural proteins that work to build new virus particles.

When the new virus particles are complete, the virus needs a way to release them to infect more cells. 'Lytic' viruses simply burst out, releasing all their virions in one huge pop and killing the cell in the process. 'Lysogenic' viruses release new virions one by one, allowing the host cell to survive and reproduce. Some viruses even stitch their genetic code into the code of their host, so that every time the cell divides, the new cells also get a copy of the viral genes. This allows viruses to remain inside cells for a long time, staying dormant and then reactivating later, a property known as latency.

Cells do attempt to defend themselves from this type of attack. They destroy loose genetic

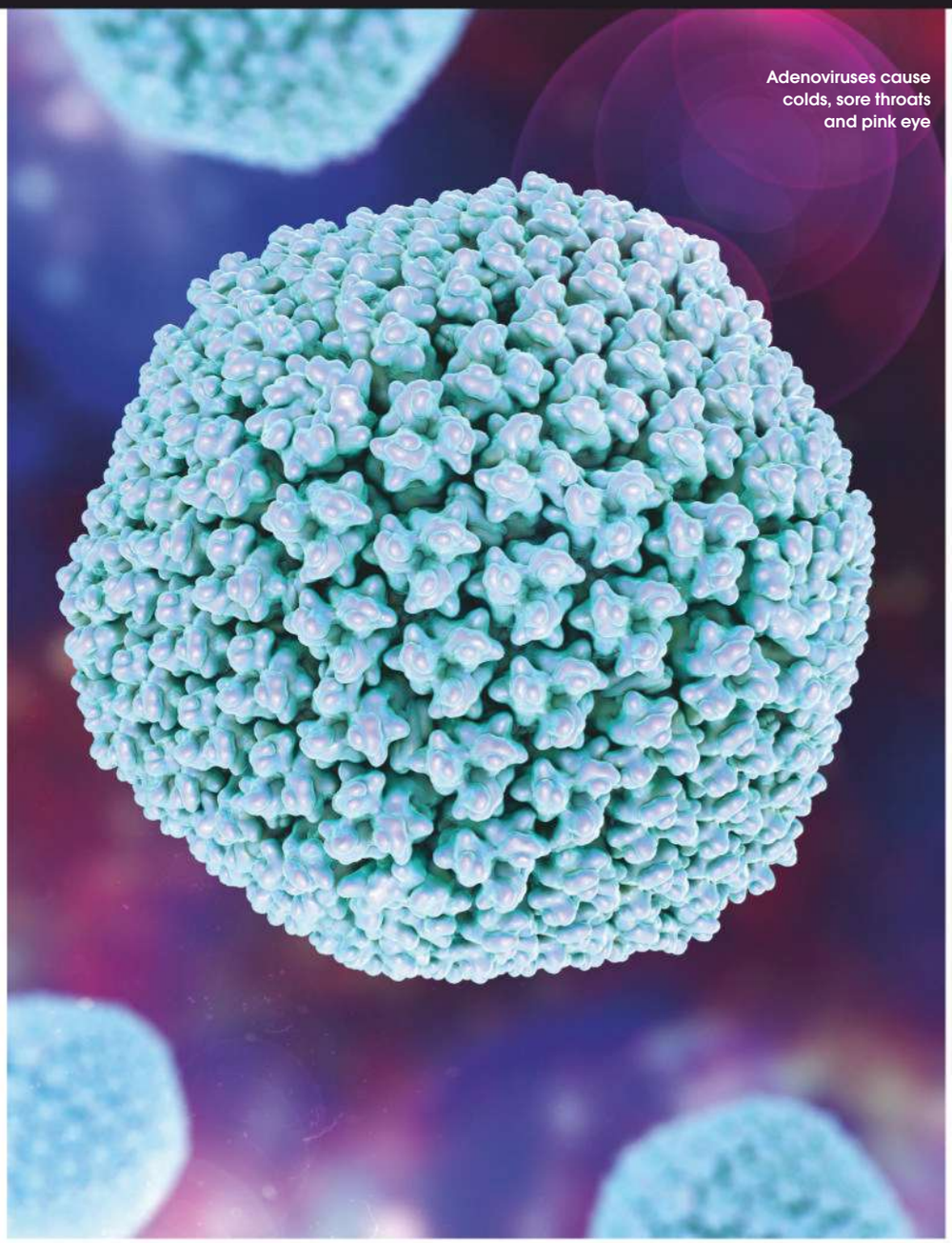
code and send signals to the immune system to let it know about the infection. But viruses have evolved ways to evade these defences – in the process, some have gained characteristics that harm their hosts, a property that is known as virulence.

Many viruses cause disease, diverting healthy cells away from their normal activities. The type of damage a virus does depends on the cells it infects, the way it interferes with molecular machines and the way it releases new virions. Some of the most serious problems arise when viruses infect immune cells, preventing the body from fighting back. Ebola, Marburg and HIV all harm the immune system.

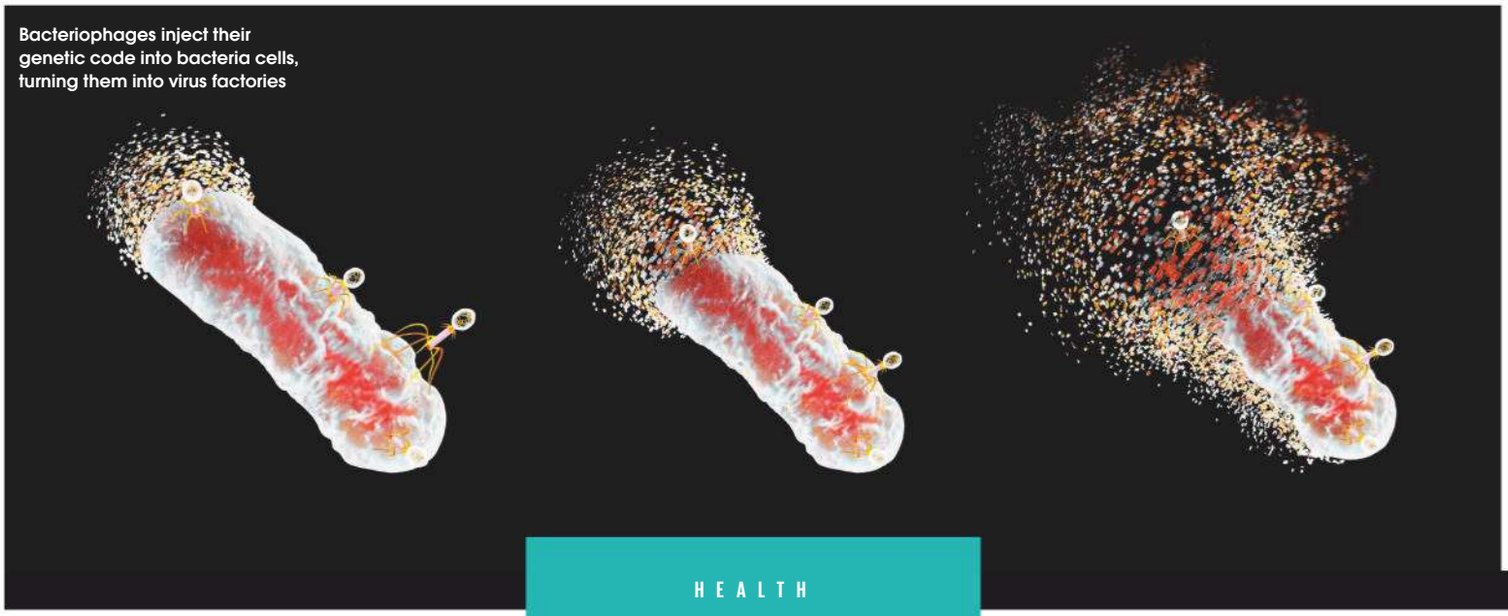
However, viruses aren't all bad; infections help to shape the way our bodies work. Studies of the human genome have revealed that around eight per cent of our genetic code actually came from viruses. Known as human endogenous retroviruses, or HERVs, they are easy to spot because they still carry the remnants of three viral genes: gag, pol and env. These genes belong to retroviruses, which stitch their genetic code into the genome of their host.

Retroviruses leave a permanent mark on DNA, and the results of ancient infections have been passed from parent to child for thousands of years. Evolution has gradually changed the sequence of these leftover viral genes, making them unable to produce new virions. Our bodies have found new uses for the code left behind.

One HERV, HERV-W, codes for proteins that would once have sat in the outer envelope of a virus, helping it to fuse with cells. We have adapted the code to make new proteins that help to fuse cell membranes together to form the placenta. Without the leftovers of ancient viral infections, we wouldn't be here today.



Adenoviruses cause colds, sore throats and pink eye



Bacteriophages inject their genetic code into bacteria cells, turning them into virus factories

Viral vectors

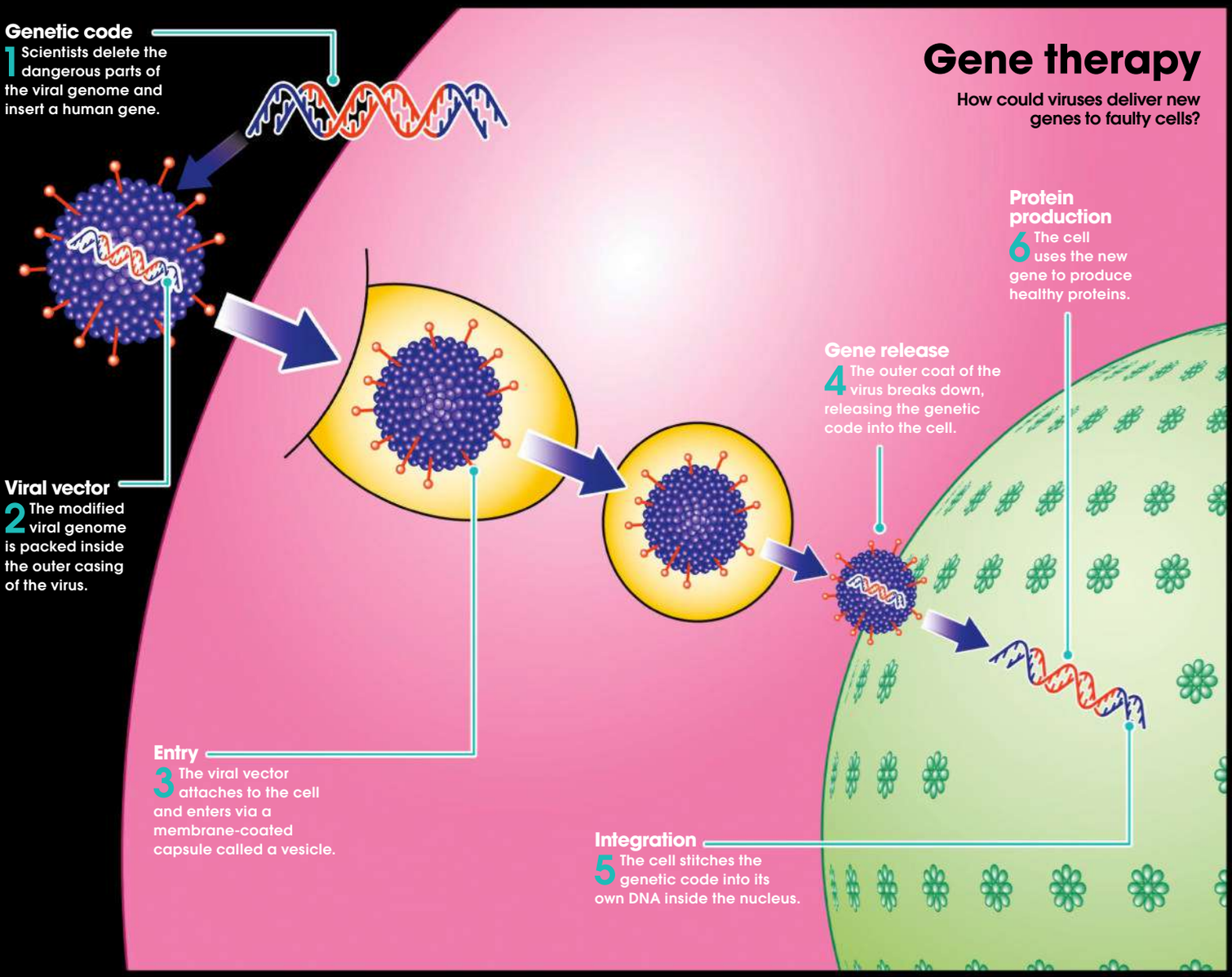
These tiny packets of genetic code are the most successful parasites in the world

Viruses specialise in getting past cellular defences to deliver genetic information into cells, but in nature, they often contain genes that cause disease. However, if we strip out these damaging stretches of code we could use the outer virus packaging to deliver useful genes to damaged cells. This is the idea behind viral vectors.

The first step requires scientists to delete the parts of the viral genome that allow viruses to make copies of themselves. Then they add the code for different genes. When the modified virus infects a cell, it carries these new genes with it.

The most commonly used viruses for vector science are adenoviruses and retroviruses. Adenoviruses have a DNA-based genome and temporarily infect mammalian cells. The cells make viral proteins for a short time and then return to normal. Retroviruses are RNA-based and insert their genetic code into the genome of the cells they infect. This permanently changes the cell's DNA, making it produce viral proteins forever.

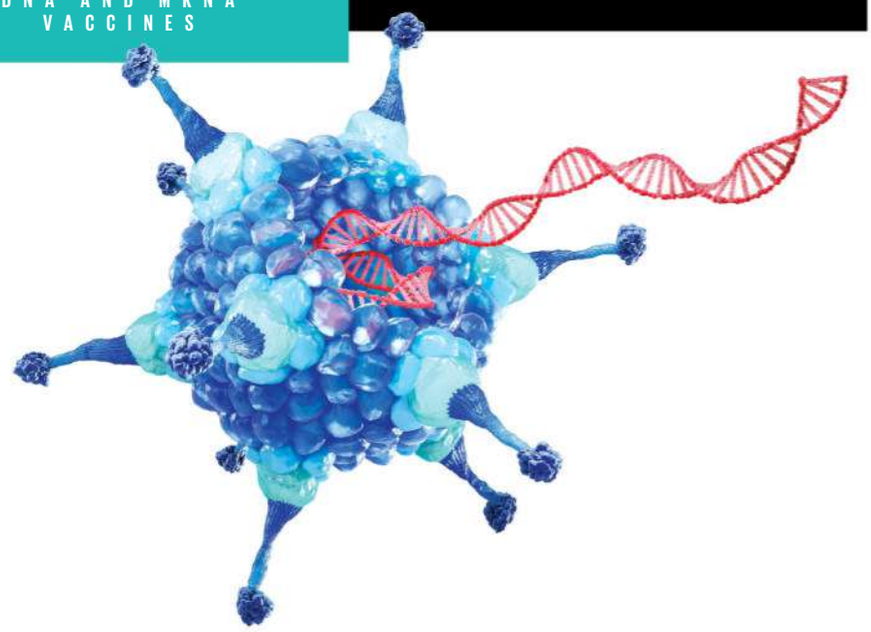
Viral vectors allow scientists to find out what happens when cells gain the ability to make different proteins. They also have the potential to fix broken genes by delivering fresh genetic code to human cells. However, the technology may be dangerous because it's hard to control precisely where the cell puts the new genes. Research is ongoing to discover if we can safely use viruses for gene therapy.



DNA and mRNA vaccines

Everything you need to know about this landmark form of immunisation

HEALTH



DNA and mRNA vaccines are two new forms of vaccine (relatively speaking) which represent exciting advancements in medical science, harnessing the power of our cells and our immune systems to fight against various diseases.

DNA vaccines, as the name suggests, introduce a small piece of DNA directly into our cells, which contains instructions for making a specific protein that triggers a desired immune response. If you imagine the DNA a little bit like a set of blueprints: once they're inside the cell, it's like someone's handing an engineer detailed plans to construct a model version of the enemy. The immune system then learns to recognise this model, so it's prepared for it if it encounters the real threat later.

mRNA vaccines take an ever-so-slightly different approach. Instead of using DNA, they use something called messenger RNA (mRNA), which acts a bit like a one-off text message with instructions. This mRNA is delivered straight into cells, instructing them to produce a specific protein, which they immediately set about doing. The immune system then learns to recognise this protein and build defences against it.

Both vaccine types leverage our body's natural capabilities and processes to prepare us for future infections, offering a new way to protect against diseases and threats.

How they were made

The development of DNA and mRNA vaccines is the fruit of decades of seriously intense scientific research and inspired innovation. The idea was first conceptualised back in the 1990s. Though theoretically promising, early DNA vaccines faced significant challenges, such as effective delivery and reliable cellular uptake. Eventually, both issues were ironed out in the lab.

"Both vaccine types leverage our body's natural capabilities and processes to prepare us for future infections"

The breakthrough for mRNA vaccines came a little while later, during the 2000s. Pioneers such as Katalin Karikó and Drew Weissman led the work, focusing on stabilising mRNA molecules and improving their delivery into cells, thereby addressing previous limitations of the technology.

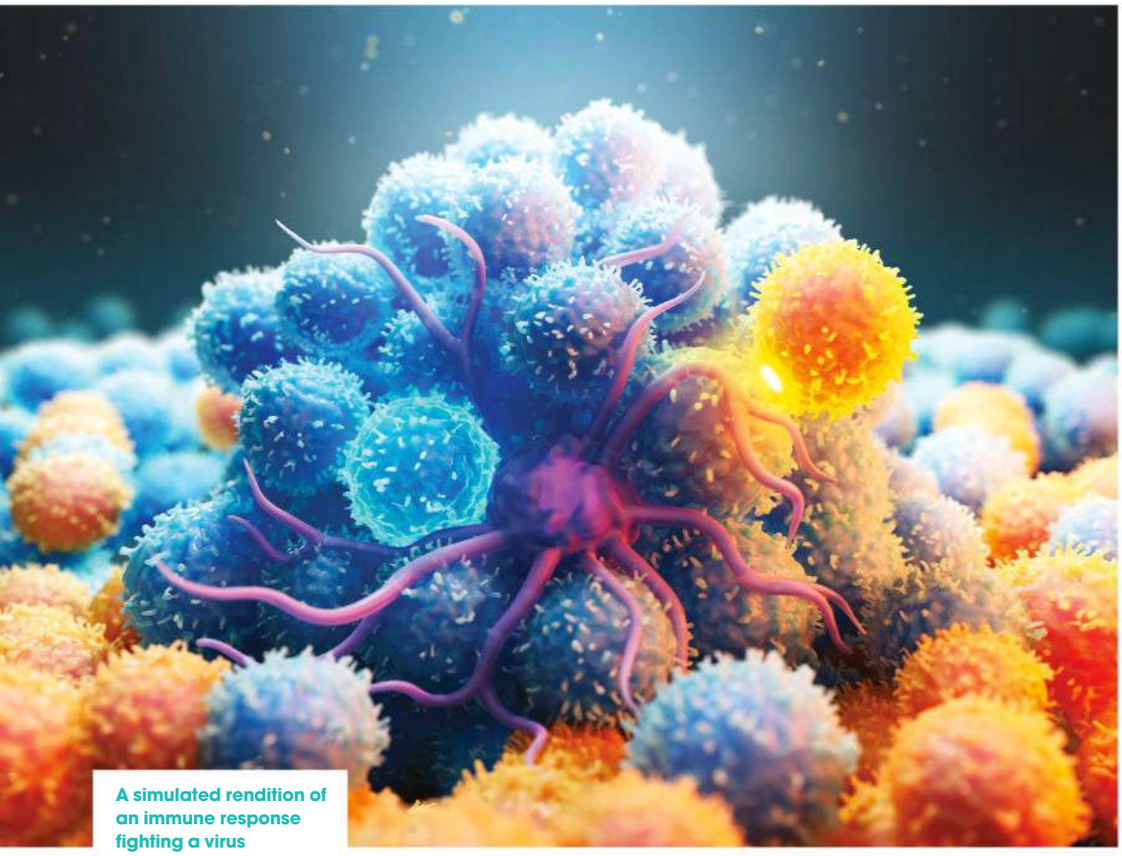
Once refined and perfected, this rather elegant solution to the many limitations highlighted by existing vaccines marked a significant advancement in vaccine tech. It also offered up a versatile and reliable platform that could be adapted for attacking various other pathogens in the future. This progress, specifically in mRNA technology, is considered by many in the field of immunology as a giant leap forward.

How they differ from typical vaccines

DNA and mRNA vaccines are distinct from traditional vaccine types, which tend to use weakened – or what's referred to as 'inactivated' – forms of a virus to stimulate immunity. Traditional vaccines work by introducing a harmless version of the pathogen, designed to prompt the immune system to recognise and remember it later.

DNA and mRNA vaccines deliver a set of instructions to our cells, stimulating an immune response

© Getty



A simulated rendition of an immune response fighting a virus

Can mRNA vaccines alter our DNA?

A quick look at one of the more worrying rumours

Amid the whirlwind of recent vaccine innovation and controversy, mRNA vaccines have taken centre stage, grabbing headlines but also causing a few furrowed brows and a little unease in certain quarters. The big worry is that they may be able to alter our DNA. Scientists are fairly convinced that's not possible, though.

mRNA vaccines, like those created for COVID-19 by Pfizer and Moderna, deliver a snippet of genetic code to our cells, teaching them to make a protein that provokes an immune response to fight the disease or virus. This mRNA never actually enters the cell's nucleus, though – which is where our DNA happily resides. Instead, it stays in the cell's cytoplasm and is eventually broken down and then discarded.

Provided the science around their inability to infiltrate the nucleus remains the case, mRNA vaccines can't integrate into our DNA. So our genetic blueprints should remain untouched. The ingenuity of mRNA technology lies in its simplicity and safety, offering a swift response to emerging pathogens without ever tampering with our genetic core.

In contrast, DNA and mRNA vaccines use genetic material to directly instruct our cells how to behave when threats are encountered. These vaccines insert a piece of DNA into cells, which produces a protein designed to trigger an immune response. mRNA vaccines use messenger RNA to deliver instructions to cells, telling them to make a protein that the immune system can recognise and then attack. That's quite different to how all other vaccines work.

The advantages

DNA and mRNA vaccines offer a few key advantages over traditional vaccines. As seen with COVID-19, the fact that they can be developed quickly (because they don't require growing large amounts of the virus or its proteins) is invaluable. This makes them highly adaptable to new pathogens.

Both types also provide precise targeting by instructing cells to produce specific proteins that stimulate an immune response. Plus, they have a fairly simple production process, which can be scaled up efficiently. This kind of flexibility and speed in development is crucial for responding rapidly to emerging health threats.

The disadvantages

Getting the actual genetic material fully into cells effectively can be a tricky process because it often requires quite advanced delivery methods.

mRNA vaccines, although very innovative, can also face stability issues at times. The mRNA must be protected from degrading before it reaches cells, which isn't always easy – or even possible.

Both types of vaccine also require reliable cold storage, and that can complicate distribution and logistics, especially when it comes to delivery to less-accessible areas.

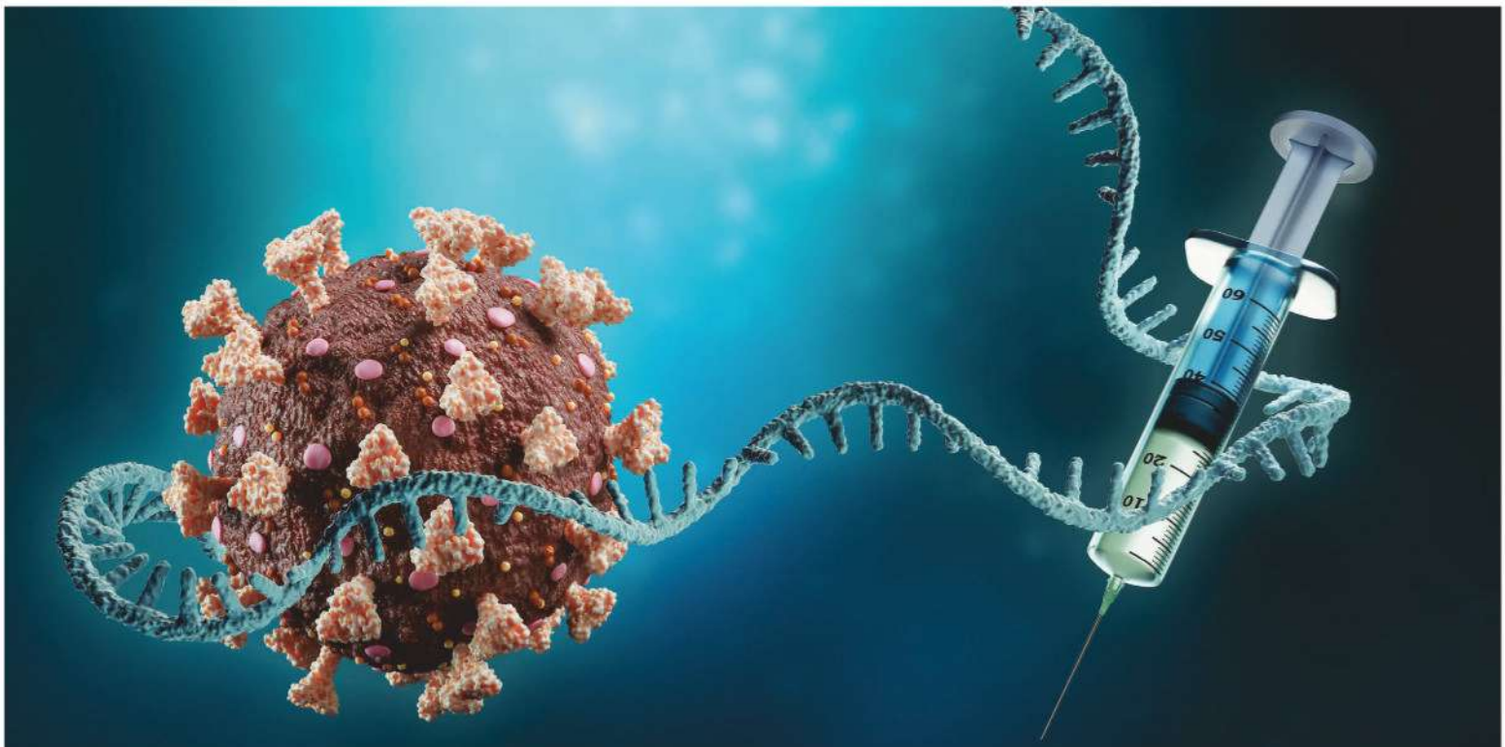
mRNA vaccines were key in fighting back the Covid-19 virus during the global pandemic

Plus, there's still some ongoing research needed to fully understand the long-term effects and safety of both DNA and mRNA vaccines.

Their role in the Covid-19 pandemic

It wouldn't be much of an overstatement to say that during the Covid-19 pandemic, DNA and mRNA technologies played pivotal and groundbreaking roles. These enabled scientists to develop a vaccine response at an unprecedented speed, using genetic instructions to prompt cells to produce the virus's spike protein, training the immune system to recognise and fight the actual virus if and when it came into contact with it – as well as deal with emerging virus variants.

mRNA vaccines, such as those from major pharmaceutical companies such as Moderna and Pfizer, pioneered with their impressively rapid production and (relative) effectiveness. These vaccines showcased the potential of genetic technology to respond quickly to emerging threats and provide an invaluable tool in controlling future disease breakouts, epidemics and pandemics.



Vaccine types

Explore the different applications of vaccine

Live-attenuated vaccines

These use a weakened but still 'live' form of the pathogen or virus to stimulate an immune response without actually causing the disease. These vaccines closely mimic natural infections, generally providing strong, long-lasting immunity. They require very careful handling and may not suit immunocompromised people.

Examples

Measles, mumps, rubella (MMR) and the famous oral polio vaccine.

Toxoid vaccines

These vaccines rely on toxins created from inactivated bacteria, which means the toxins can't cause the actual disease itself. These vaccinations help the immune system identify and fight the poisons present during an illness. Booster doses are sometimes necessary to maintain long-term protection, and they are safe and effective.

Examples

The two biggest toxoid vaccines out there are those used to fight diphtheria and tetanus.

Inactivated vaccines

Inactivated vaccines are made from germs or viruses that have been killed, rendering them unable to cause disease in the body. These vaccines trigger an immune response by exposing the body's defences to the inactivated pathogen. They typically require multiple doses to achieve and maintain effective immunity.

Examples

The inactivated polio vaccine (IPV), hepatitis A and rabies vaccine.

Viral vector vaccines

Viral vector vaccines use a totally harmless modified virus (not the disease-causing one) to deliver genetic material from a pathogen, prompting an immune response. The vector virus infects cells and instructs them to produce antigens, triggering immunity. These vaccines tend to be pretty effective and can – crucially – be developed very quickly.

Examples

Examples of VVVs include the Ebola vaccine and Johnson & Johnson's COVID-19 vaccine.

Subunit vaccines

Because they tend to have fewer side effects, subunit vaccines are safer for people with weakened immune systems. They contain only specific parts of a pathogen that best stimulate the immune system, such as proteins or sugars. These components are enough to provoke a protective immune response without risking infection at all.

Examples

Common examples of some subunit vaccines include the hepatitis B and human papillomavirus (HPV) vaccines.

mRNA vaccines

mRNA vaccines use a synthetic version of an RNA molecule to instruct cells to produce a protein from a pathogen, which triggers an immune response. This teaches the immune system to recognise and combat the actual pathogen when it encounters it. mRNA vaccines are claimed to be safe, do not use live viruses and can be developed fairly rapidly.

Examples

Pfizer and Moderna's COVID-19 vaccines are famous examples of mRNA vaccines.

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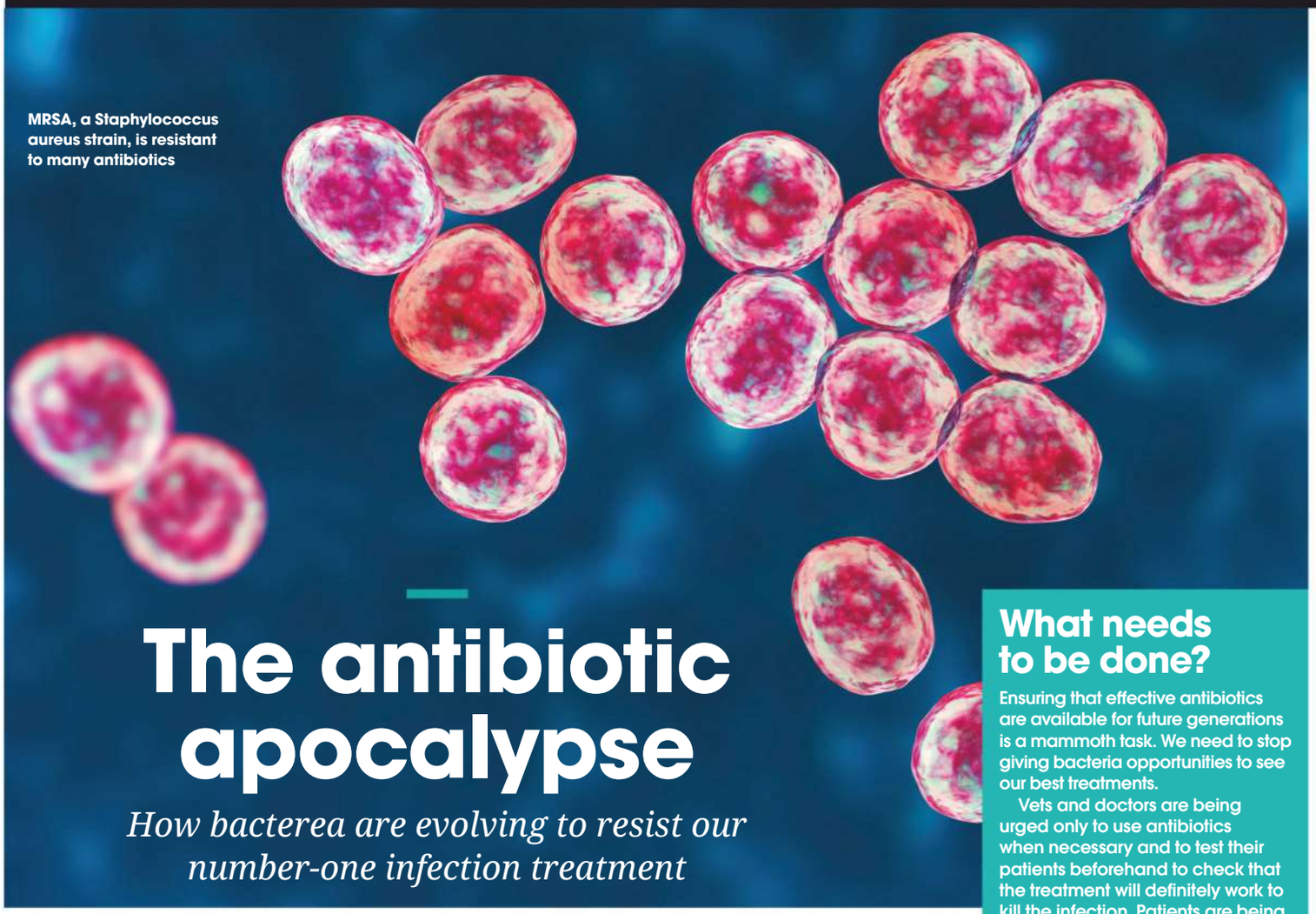


MRSA, a Staphylococcus aureus strain, is resistant to many antibiotics

The antibiotic apocalypse

How bacterea are evolving to resist our number-one infection treatment

We have a major problem. Since the dawn of humanity, we have been locked in a battle with microscopic organisms, and just when we thought we were starting to win, they're fighting back.

Bacteria cause some of the most devastating human diseases, from typhoid fever to tuberculosis, and until the 1920s we were utterly defenceless. But when Alexander Fleming ushered in the age of the antibiotic with his discovery of penicillin, we suddenly had a powerful weapon.

Antibiotics work by stopping bacteria from dividing or by killing them outright. Thanks to them we can treat infections that were once fatal, we can perform complex surgery, and we can mass-produce food on an unprecedented scale. But we have used them and used them and used them, and the bacteria have started to learn to fight back, with dire consequences.

These little organisms can replicate in a matter of hours, and each time they do, they make tiny, accidental tweaks to their genetic code. Some tweaks aren't useful, but very occasionally, a mistake is made that helps one bacterium to outlast an onslaught of antibiotics for just a little longer than their neighbours.

When the course of antibiotics is finished, and all of the vulnerable bacteria are dead, this slightly stronger individual can carry on dividing, making a new colony that is better at avoiding the effects of the drugs. And if this happens time after time, you soon have a superbug on your hands.

Worse still, bacteria are able to share useful genes with their neighbours. And not just members of their own species. They carry useful snippets of genetic code in little rings of DNA called plasmids, which they can swap like trading cards, passing their antibiotic resistance blueprint on to others around them.

Using these tactics, several strains of bacteria are now able to evade almost all of the antibiotics in our arsenal. We're in the middle of a microscopic arms race, and the future of medicine is hanging in the balance.

What needs to be done?

Ensuring that effective antibiotics are available for future generations is a mammoth task. We need to stop giving bacteria opportunities to see our best treatments.

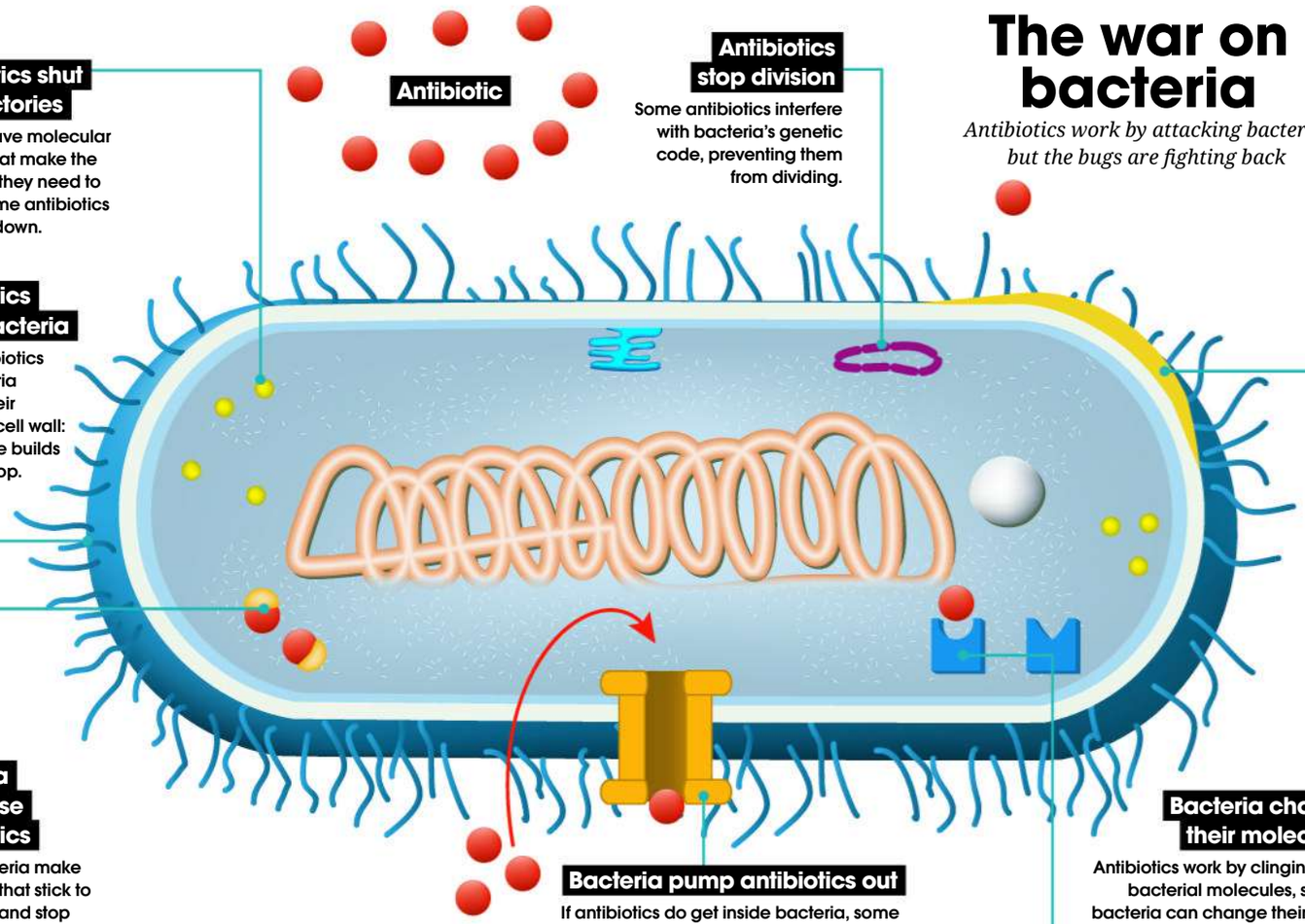
Vets and doctors are being urged only to use antibiotics when necessary and to test their patients beforehand to check that the treatment will definitely work to kill the infection. Patients are being asked always to finish their full course of antibiotics, even if they feel better, to ensure that any lurking bacteria are cleared up. Farmers are being encouraged to keep their livestock clean and vaccinated rather than use antibiotics to control disease.

Governments and development organisations are under pressure to regulate and monitor antibiotic use, and to make sure people have access to the right antibiotics. And the medical research community is racing to find new drugs to fight resistant strains. Rather than throw antibiotics at any infection, we need to choose our battles more carefully.

Antibiotics are used everywhere, from hospitals to intensive farms

The war on bacteria

Antibiotics work by attacking bacteria, but the bugs are fighting back



Antibiotics shut cell factories

Bacteria have molecular factories that make the molecules they need to survive. Some antibiotics shut them down.

Antibiotics stop division

Some antibiotics interfere with bacteria's genetic code, preventing them from dividing.

Antibiotics burst bacteria

Some antibiotics stop bacteria building their protective cell wall: the pressure builds and they pop.

Bacteria neutralise antibiotics

Some bacteria make molecules that stick to antibiotics and stop them working.

Bacteria pump antibiotics out

If antibiotics do get inside bacteria, some are able to pump them straight out again.

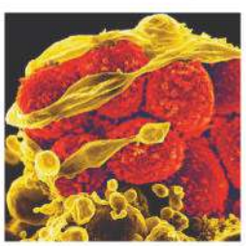
Bacteria change their molecules

Antibiotics work by clinging on to bacterial molecules, so if the bacteria can change their shape they can sometimes escape.

Bacteria block antibiotic entry

Some bacteria have developed ways to stop antibiotics from getting through their cell walls.

Superbug lineup



MRSA

Methicillin-Resistant Staphylococcus aureus (MRSA) is the most infamous of all superbugs, thanks to its potency in hospitals. Regular Staphylococcus aureus is a common bacteria, normally found harmlessly on human skin. This bug first started resisting the effects of antibiotics as far back as the 1950s, however, and MRSA itself first appeared in 1962.

VRE

Vancomycin-resistant Enterococcus (VRE) is immune to the effects of one of our most powerful antibiotics. Vancomycin is usually reserved for the most serious of infections, including meningitis and MRSA. VRE superbugs were first spotted in the 1980s; they colonise your bowels and have proven very good at developing resistance to any new antibiotics thrown at them.

MDR-TB

Multi-Drug-Resistant Mycobacterium tuberculosis (MDR-TB) does not respond to the two most powerful anti-tuberculosis drugs currently available — rifampicin and isoniazid. Normal treatment for TB involves a combination of antibiotics taken for six months, but if the drugs are given alone or stopped too soon, resistance can develop.

KPC

Klebsiella pneumoniae carbapenemase-producing bacteria (KPC) are a relatively new problem compared to the other bugs on this list, first identified in the US in the early 2000s. They are very good at resisting treatment and also produce an enzyme that enables them to break down carbapenem, a powerful antibiotic that's one of our last lines of defence.

Learn more

Arm yourself with information

Knowledge is the most powerful weapon we have against an antibiotic apocalypse. Here are two top places to learn more:

The World Health Organisation

www.who.int

Working in over 150 countries, the World Health Organisation is leading the fight against antibiotic resistance. Its social media accounts are a great place for bite-sized news and updates.

Bugs and Drugs

www.antibioticresistance.org.uk

With funding from the British Government's Department of Health, the National Electronic Library of Infection have made a one-stop hub of information about antibiotic resistance.

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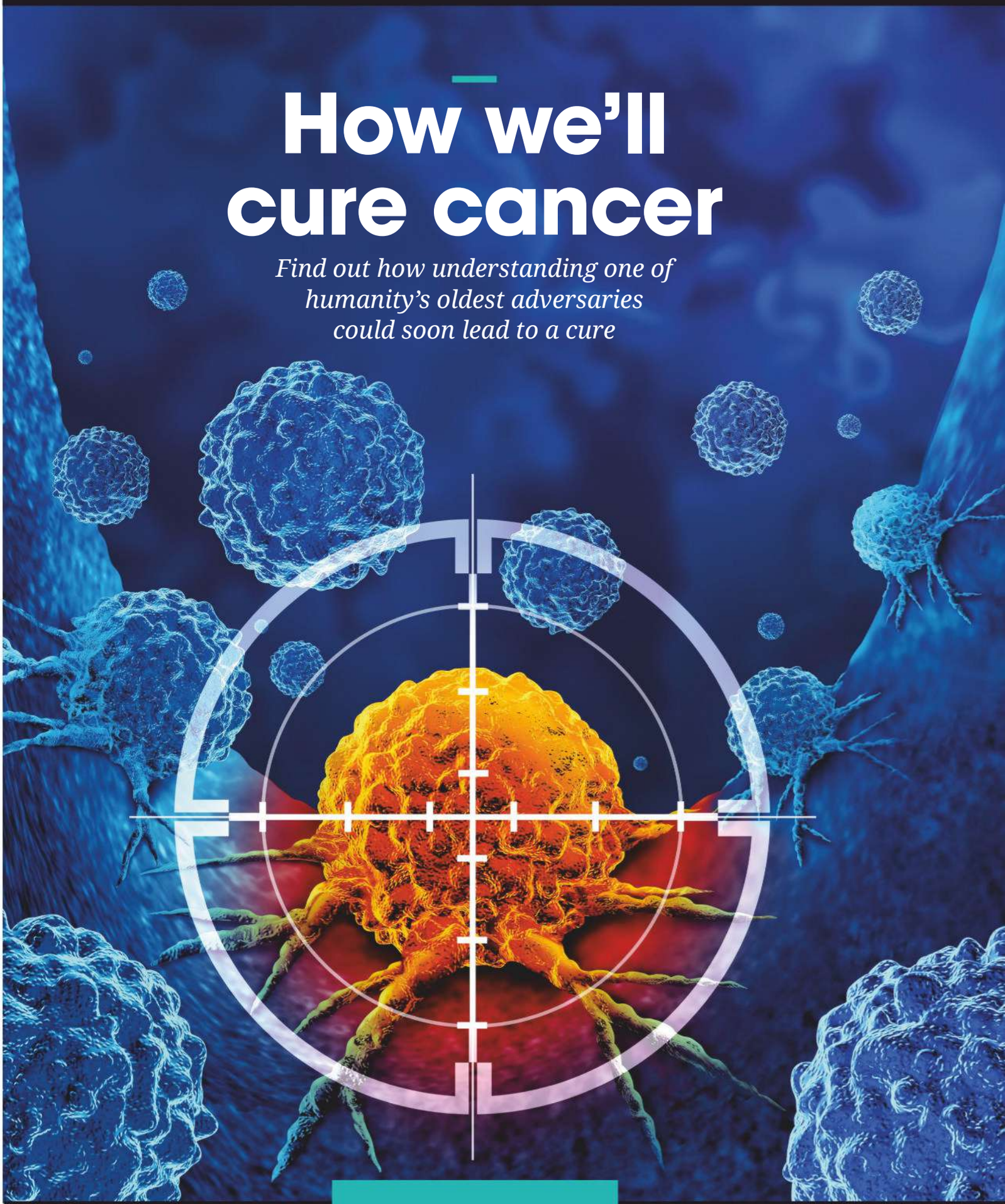
How we'll cure cancer

Find out how understanding one of humanity's oldest adversaries could soon lead to a cure



HEALTH

Cancer has been around longer than we have. Traces have been found in 70-million-year-old dinosaur bones, in a 120,000-year-old Neanderthal rib, and in a human skeleton dating back to 1200 BCE. And almost every animal – even sharks and naked mole rats – can get the disease.

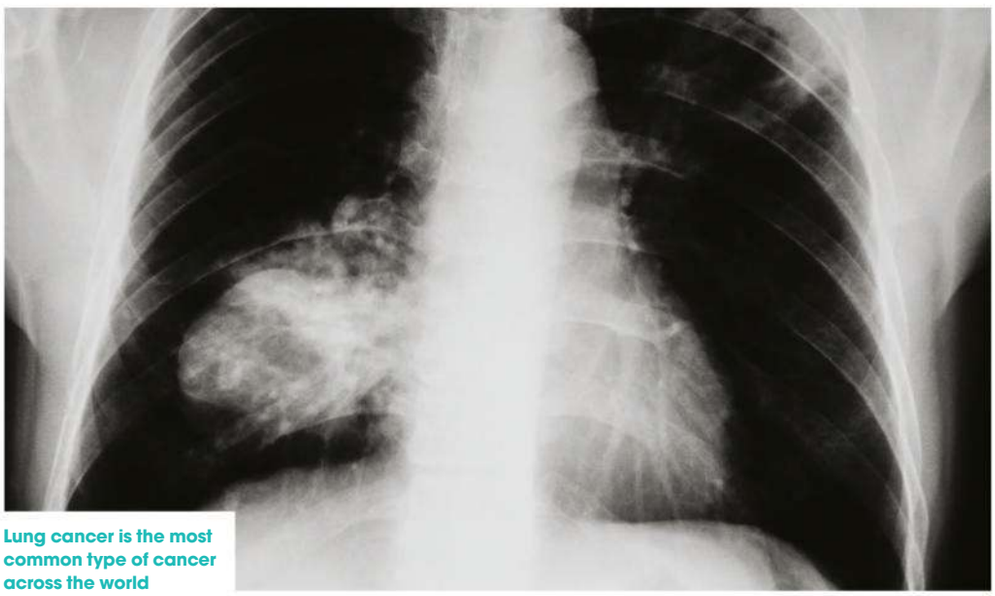
It was once untreatable. Ancient Roman doctor Celsus wrote, "After excision, even when a scar has formed, nonetheless the disease has returned." Even if the tumours were removed, they kept coming back, but in ancient times, we didn't fully understand exactly what we were up against. By the 17th century, physicians were pointing the finger at a straw-coloured liquid called lymph, which passes through the body in channels that run alongside the blood vessels. And by the mid-1800s, it became clear that cancers were actually made from cells.

Realising that cancer had spread from the original tumour, 19th-century surgeons, with the help of anaesthetics, started removing more tissue and lymph nodes. Then, at the start of the 20th century, radiotherapy became available to treat irremovable cancers. Nitrogen mustards then became the first chemotherapy drugs after WWI. Then a massive breakthrough was made. In 1953, James Watson and Francis Crick deciphered the structure of DNA, opening the door to a new era of genetic science. We now know that tumours are made of our own cells, but their genes have gone wrong. They change constantly, they evolve to escape treatments, and they hide and spread undetected. And the more we learn, the more we are unravelling their weaknesses.

A century ago, a cure for cancer would have been unthinkable, but as research continues, survival is rising, and there are many more discoveries yet to be made.

"Watson and Crick deciphered the structure of DNA"

Damage builds up in our DNA over time, making cancer more common in older people



Lung cancer is the most common type of cancer across the world

Cancer statistics

18 million

people were diagnosed with cancer in 2020

33%

of cancer deaths are caused by smoking

10 million

people died from cancer in 2020

70%

of cancers happen in low and middle income countries

Cancer is the second highest cause of death in the world

Up to half of all cancers can be prevented by lifestyle changes

Lung cancer is the most common worldwide, followed by breast and colon

Australia has the highest cancer rate

© Getty; Thinkstock

What is cancer?

The first step to finding a cure is understanding exactly what we're up against

You're made up of an estimated 37.2 trillion cells, each containing an entire copy of your DNA, which consists of 23 pairs of chromosomes and 21,000 genes, written in combinations of four chemical 'letters': A, C, G and T.

The full human DNA sequence contains around 3 billion letters, and the genes are arranged into three-letter 'words' called codons. Each word corresponds to a molecular building block called an amino acid and, when genes are read in order, the words in a gene provide the recipe to build a protein. Proteins are crucial for everything that a cell does, from making energy to deciding when to divide to communicating with its neighbours. But in cancer cells, vital genes contain mistakes, changing their proteins and altering the way that they behave.

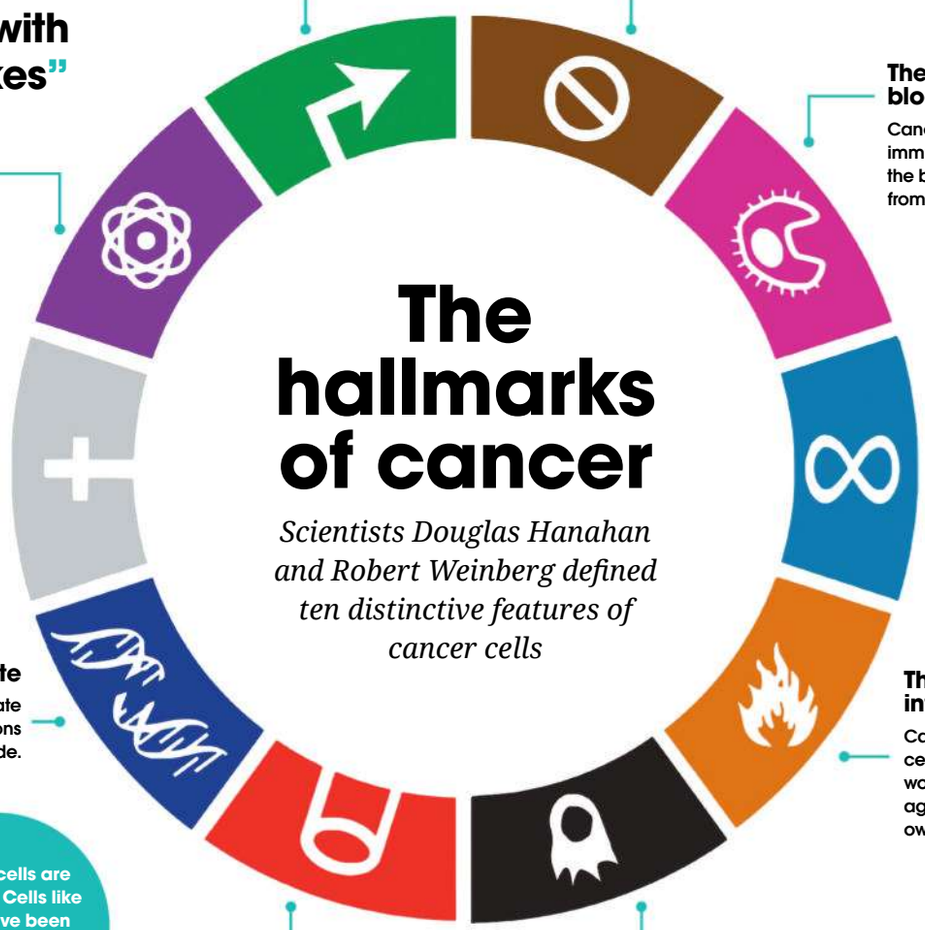
It takes lots of genetic mistakes to turn a healthy cell into a cancer cell, and they tend to build up over time. A few people inherit genetic faults from their parents, but most occur as we get older. Sunlight, alcohol, radiation and smoking, for example, can all cause harm to our genetic code. But even people with the healthiest lifestyles accumulate genetic faults.

Cells divide for growth and repair, making copies of themselves to replace old cells or to heal wounds. In order to do this, a cell must first duplicate all 3 billion letters of its DNA, and doing this without making a single mistake is a virtually impossible task.

"Cancer cells keep making copies of themselves with more mistakes"

The hallmarks of cancer

Scientists Douglas Hanahan and Robert Weinberg defined ten distinctive features of cancer cells



They keep growing
Cells normally wait for a signal to divide, but cancer cells make their own growth signals.

They don't stop when told
Cancer cells ignore signals telling them to stop dividing.

They avoid white blood cells
Cancer cells hide from the immune system, preventing the body's natural defences from killing them.

They are immortal
Normal cells stop dividing when they become old, but cancer cells keep on replicating indefinitely.

They create inflammation
Cancer cells hijack immune cells, using inflammation that would normally help to fight against an infection to their own advantage.

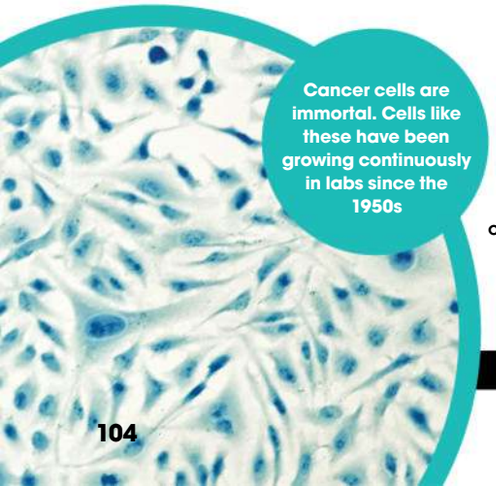
They spread
Cancer cells can spread around the body, creating more tumours in other places.

They set up fuel lines
As tumours grow, they get more oxygen and nutrients by encouraging new blood vessels to form.

They mutate
Cancer cells accumulate more and more mutations as they continue to divide.

They resist death
Healthy cells self-destruct when they are damaged, but cancer cells turn this safety switch off.

They change their metabolism
Cancer cells reprogram their metabolism to keep dividing under conditions that would normally kill other cells.



Cancer cells are immortal. Cells like these have been growing continuously in labs since the 1950s

The copied code is scanned for errors, and mistakes are usually fixed before the cell divides, but sometimes errors slip through and over time they start to build up.

Just as changing the letters in a book would make the words unreadable, changing the letters in the genetic code makes it hard for the cell to make sense of its genes. If letters are changed, deleted, added or moved around, it can completely change the meaning of the genetic words, which changes the proteins that the cell makes.

Built-in safety mechanisms normally tell a cell to self-destruct if it has too many genetic errors, allowing a new, healthy cell to take its place. But sometimes, damaged cells slip through the net, failing to repair themselves and resisting the signals to die.

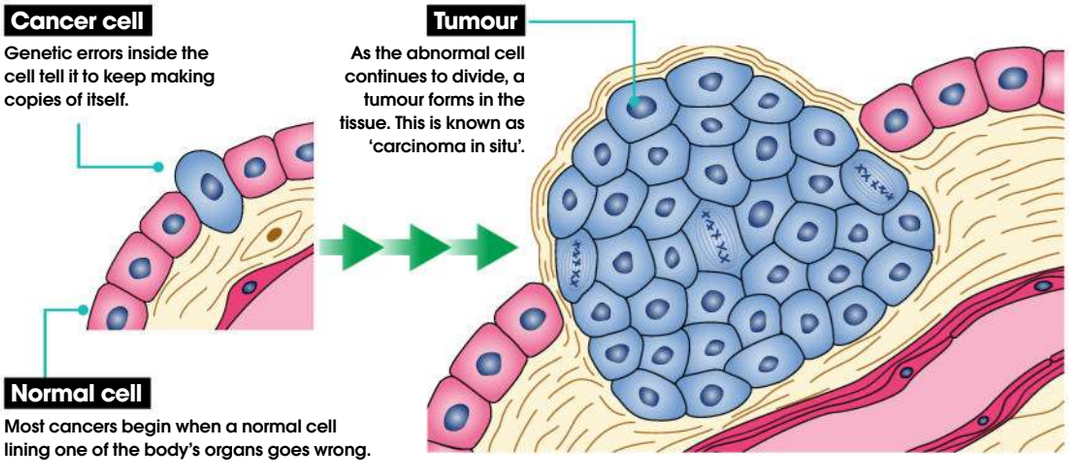
Cancer cells tend to have errors in genes known as 'oncogenes' or 'tumour suppressor genes'. Oncogenes are responsible for telling healthy cells to divide, helping with growth and wound repair, but mutations can cause them to become permanently switched on. Tumour suppressor genes, on the other hand, tell cells to stop dividing once growth or repair is completed, and errors in these genes can cause them to turn off. The result is that the damaged cells divide and divide, piling up on top of one another, forming a tumour.

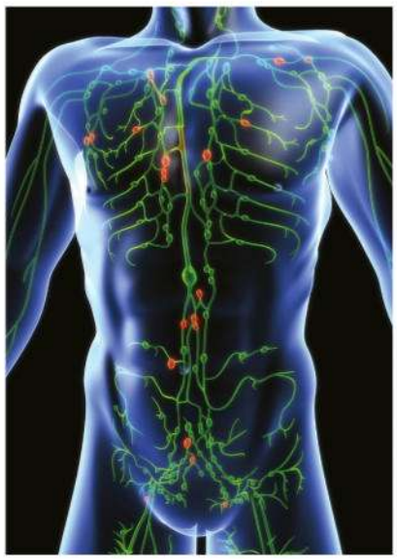
With their safety systems switched off and nothing to tell them to stop, cancer cells keep making copies of themselves with more mistakes in their genetic code, and this leads to Darwinian evolution at a rapid speed. Just as if a wild animal has a beneficial genetic trait it will be more likely to reproduce, if a cancer cell has a beneficial trait it will be more likely to survive.

Cancer cells gain new abilities, developing traits that allow them to hide from the immune system, survive on less oxygen, and even evade chemotherapy. But, most dangerous of all, they gain the ability to move through the body, spreading to distant places via the blood or lymphatic systems and making new tumours elsewhere. But the more we understand about how cancer works, the better we are becoming at treating it.

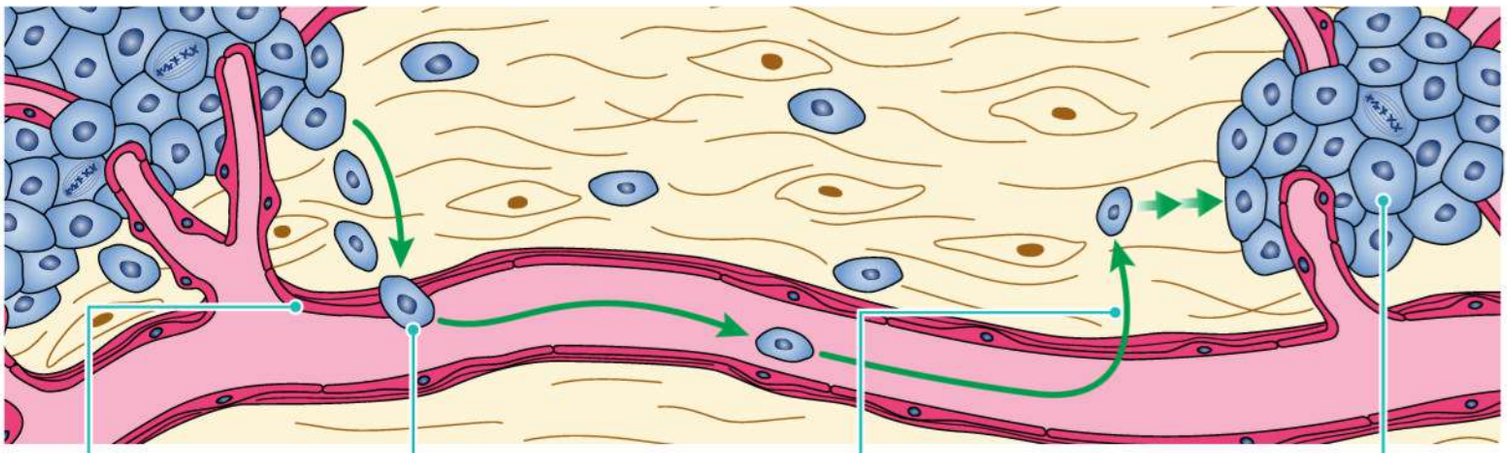
How cancer starts

Cancer begins with a single mutated cell that divides and spreads





Cancer cells can use the lymphatic system to spread around the body



Blood vessels
To keep growing, the tumour needs a blood supply, so it encourages the formation of new blood vessels.

Distant spread
Cells start to break away from the main tumour, entering the lymphatic system and the blood vessels and spreading around the body.

Local spread
Eventually, the tumour starts to invade the local tissue, growing down into the connective tissue below.

Secondary tumour
Cancer cells become lodged in different tissues and continue growing, forming more tumours known as 'secondaries' or 'metastases'.

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Treating cancer

There are three major types of cancer treatment: surgery, radiotherapy and chemotherapy

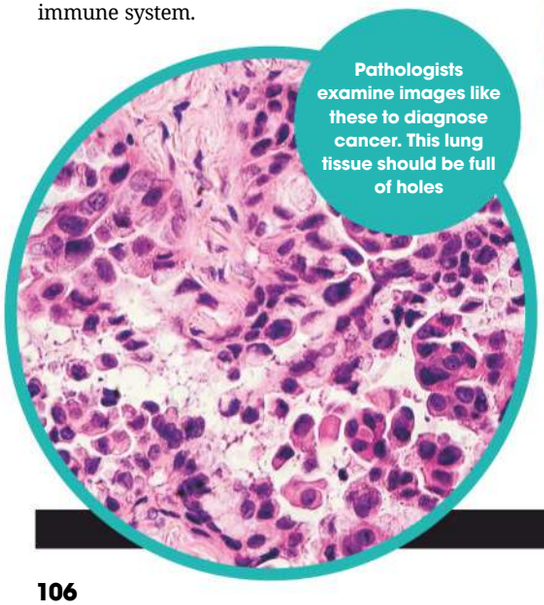
Chemotherapy

The first chemotherapy drug was developed using mustard gas, a chemical weapon used during WWI. Scientists had noticed that the poison killed the fast-dividing cells of the bone marrow, so they adjusted the weapon to make nitrogen mustard, a treatment that could kill rapidly replicating cancer cells.

Nitrogen mustard belongs to a group of drugs known as alkylating agents, which work by adding chemical units called alkyl groups to DNA. These interfere with the double helix structure, causing the genetic code to break apart.

Other chemotherapies work in similar ways. Heavy metals cross-link DNA, preventing it from being read. Topoisomerase inhibitors stop the DNA helix from unwinding, and antimetabolites work by mimicking molecules involved in copying DNA, stopping the new sequence from being made. Anti-microtubule, or spindle poisons, stop cells from splitting apart, and cytotoxic antibiotics stick to the DNA helix, prevent unwinding, link different strands of DNA together or break DNA into fragments.

These treatments are particularly harmful to cells that are trying to make copies of themselves because they target DNA replication and cell division. This is good for catching fast-dividing cancer cells, but it isn't perfect. Cancer cells aren't always dividing, so some cells manage to escape the treatment, and lots of healthy cells also divide rapidly, too. Hair, skin and bone marrow (which makes blood cells) are all damaged by chemotherapy, leading to side effects like hair loss, sickness and a weakened immune system.



Pathologists examine images like these to diagnose cancer. This lung tissue should be full of holes

Chemotherapies harm cells that are trying to divide

Radiotherapy

Radiotherapy was developed in the early 20th century and works by bombarding cancer cells with radiation. When the water molecules inside the cells are hit, they split apart in a process called radiolysis. This makes highly reactive free radicals with an unpaired electron that attacks bonds belonging to other molecules, setting off a chain reaction that damages DNA.

Radiotherapy causes both strands of the DNA to break close together, a lesion known as a 'double-strand' break. This makes the helix unstable and it starts to unwind. Cells can repair a bit of this kind of damage, but the more radiation they receive, the more likely they are to die.

The most common way to deliver radiotherapy is by using a linear accelerator (LINAC). It uses microwaves to make electrons, which hit a heavy metal to make X-rays. CT or MRI scans are used to pinpoint the exact location of the tumour inside the body, and the X-rays are then shaped to fit the outline of the tumour. This is done by blocking part of the beam using sheets of metal known as a multileaf collimator.

X-rays go all the way through the body, so the machine rotates to deliver beams from all angles, giving the maximum dose where the beams cross over at the site of the tumour, minimising the amount of radiation received by the surrounding healthy tissue.

Linear accelerators rotate to deliver high-energy X-rays into tumours from all angles

Surgery

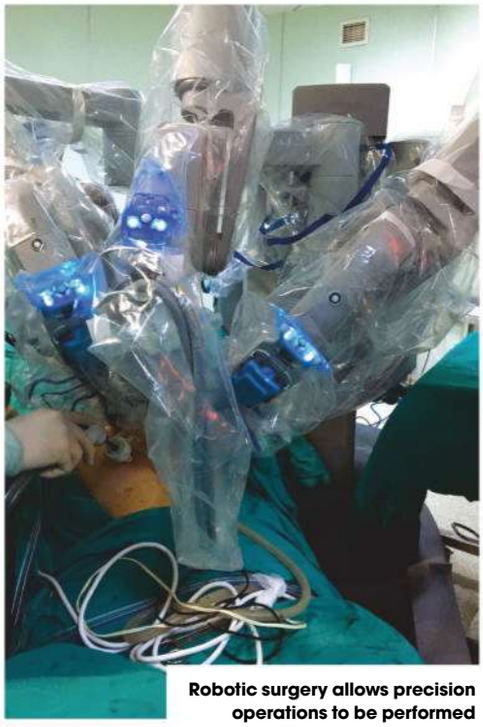
Surgery is one of the oldest and most effective cancer treatments. If the cancer hasn't spread, surgeons take out the whole tumour and some of the surrounding area in case there are any cells that can't be seen. Nearby lymph nodes may also be removed as these are often the first place a cancer will spread to.

If the whole tumour cannot be removed, surgery can also be used for 'debulking', where as much of the tumour is removed as possible so the rest can be treated with chemotherapy or radiotherapy. Surgery can also be palliative, relieving symptoms when cancer cannot be cured.

Not all lumps are tumours and not all tumours are cancer, so surgery is often used for cancer diagnosis, too. A small sample of tissue, known as a biopsy, is removed and either frozen solid or embedded in wax so that it can be thinly sliced. These slices are stained so that a pathologist can examine the structure of the cells and tissue.

Cancer cells look different under a microscope, creating disorganised structures in normally orderly tissues, and they also display specific molecular or genetic markers that single them out. These not only help with a cancer diagnosis but can also be used to determine the type of cancer, how advanced it is and the best form of treatment to use against it.

Scans are used to find the exact location of a tumour for surgery or radiotherapy



Robotic surgery allows precision operations to be performed

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The future of cancer treatment

The more we learn about cancer, the better we are able to target its weaknesses

In the UK, overall cancer survival is now at 50 per cent, and ten-year survival for testicular cancer has reached an impressive 98 per cent. But there's still a way to go. There are hundreds of cancer types, and even patients with the same type have subtle differences in their tumours that change their response to treatment. Cancers can become resistant to chemotherapy and radiotherapy, and many treatments also harm healthy cells, causing side effects that limit their use.

Until recently, most cancer treatments have focused on one thing: cell division. Both radiotherapy and chemotherapy hit rapidly dividing cells, damaging their DNA as they try to replicate, causing them to die. But cancer has lots of other weaknesses and scientists are attacking from all angles, using the latest tech to reveal their genetic and molecular differences.

One tactic is to cut cancer's fuel lines. As tumours grow and cells pile on top of one another, oxygen levels drop and the cancer cells encourage new blood vessel cells to break down tissue and migrate in. Blocking this process could stop tumour growth in its tracks.

Another option is to use the immune system, helping our own cells to see cancer cells. Techniques being trialled include using molecules to block the interaction between cancer cells and immune cells, preventing the tumour from switching the immune system off, and genetically engineering cells to supercharge their ability to seek and destroy cancer cells.

Antibodies are also being transformed into cancer treatments that should leave healthy cells unharmed. They can be made to stick to a single molecule, blocking the chemical signals that tumours need to survive or attaching directly to the cancer cells. Researchers are also working on genetically modifying viruses to infect and kill cancer cells, delivering drugs into cancer cells using nanoparticles and designing small molecules to interfere with the crucial molecular machinery that cancer cells use to survive.

It's very unlikely that there will ever be a single cancer cure, but the more we learn, the more targeted treatments will become, killing cancer cells more effectively and leaving healthy cells unharmed.

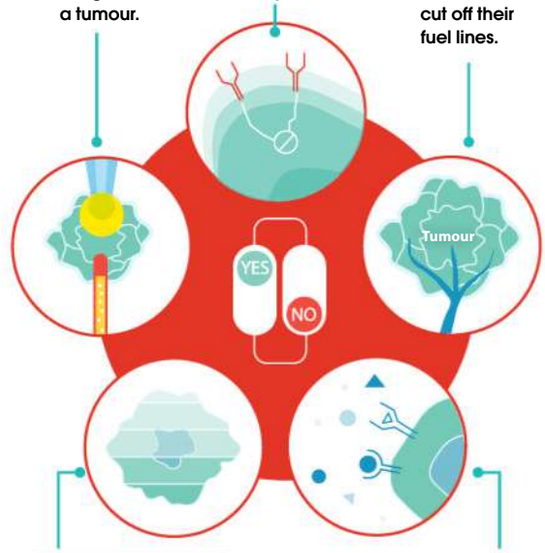
Targeting cancer's weaknesses

Modern techniques are zeroing in on the molecules and genetics that make cancer cells vulnerable

Molecular tags
Cancer cell molecules look different. Targeting these could deliver toxins straight to a tumour.

Growth signals
Cancer cells receive signals that tell them to keep growing. Blocking these could halt the process.

Blood supply
Cancer cells need a blood supply to survive. Blocking new blood vessel formation would cut off their fuel lines.



Self-destruction
Cancer cells don't die even though they are faulty. Targeted therapies could switch self-destruct systems on.

Hormones
Some cancer cells are driven by hormones. Stopping their production could slow growth.

Trawling cancer genetics
Cancers have distinctive mistakes in their genetic code that could reveal weaknesses.

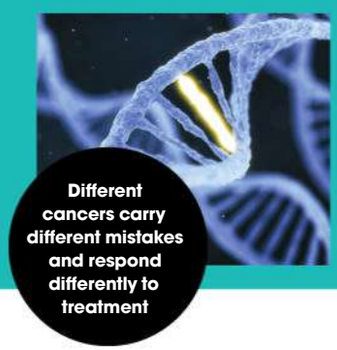
Pathology
Cancer cells can be tested for the presence of molecules that single them out as defective.

Custom treatment
Individual patients could be matched to the treatments most likely to work for their unique tumour.

Customising cancer treatment

The Human Genome Project unravelled the human genetic code in 2003. This epic sequencing mission detailed every single letter of our DNA, revealing for the first time the complete recipe book for a human body. Cancer cells read from the same recipe book as healthy cells, just with words blotted out, pages stuck together and sentences scrambled. By understanding how the recipe book is supposed to be put together, scientists are now better able to identify why and how cancer cells have got it so badly wrong.

Every person is slightly different and their cancer cells start with a different set of instructions, and as the disease progresses, different tumours adapt in unique ways. Two women might both have breast cancer, but although there are patterns of similarity, the genetics inside their cancer cells won't be exactly the same, so they don't always respond in the same way to treatment. In the future, people will be tested to reveal the targeted treatments that will work best for them.



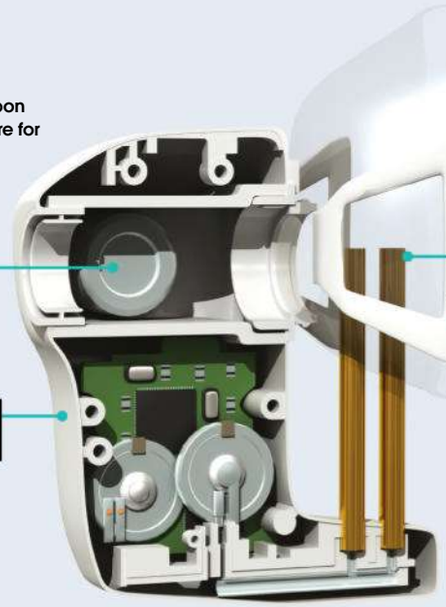
Different cancers carry different mistakes and respond differently to treatment

Catching cancer early

The sooner cancer is detected, the easier it is to treat. There are already three screening programmes in operation in the UK to detect bowel cancer, breast cancer and cervical cancer, but in the future, things could become a whole lot simpler. Research into 'biomarkers' is searching for molecular signals that could reveal cancer in a simple blood, urine or even breath test.

Biomarkers are molecular signatures unique to different types of cells. Cancer cells differ from normal cells in ways that can already be detected using biopsies of tumour tissue, but researchers think that these differences might also make their way into body fluids, allowing them to be picked up with a simple test. Biomarkers might be able to reveal clues about the best treatment to use, whether the tumour is becoming resistant to current drugs and whether cancer has returned.

"One tactic is to cut cancer's fuel lines"



Sensors
Sensors detect carbon dioxide and pressure for breath monitoring.

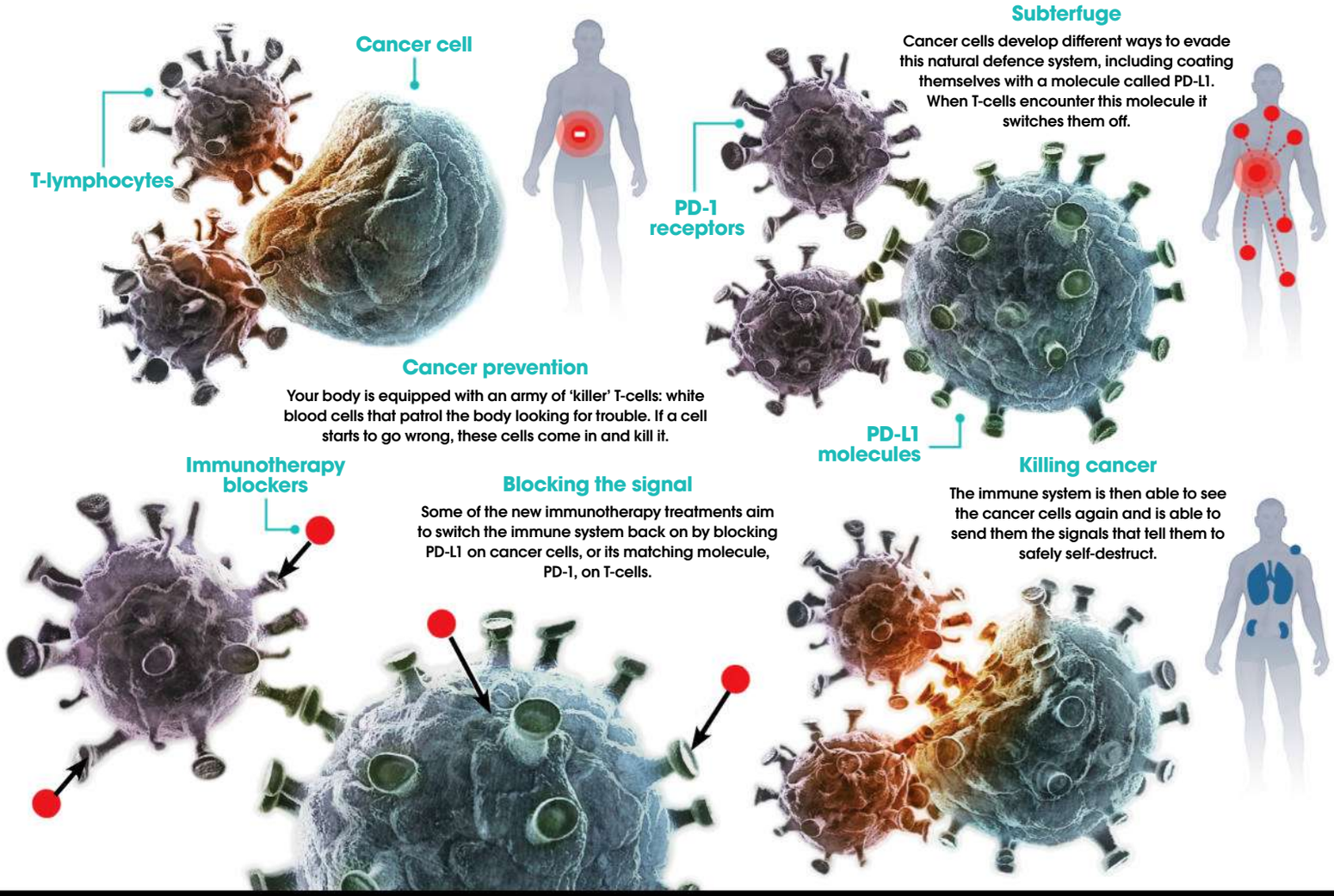
Facemask
Single-use masks with a filter are used to blow air into the device.

Sorbent tubes
The breath is separated into fractions and stored in two pairs of tubes that can be analysed in the lab.

LuCID clinical trial
The device is currently being trialled to find out whether it is effective for lung cancer diagnosis.

Volatile organic compounds
The inventors hope that detecting traces of chemicals called aldehydes and ketones could predict lung cancer.

Strengthening your immune army



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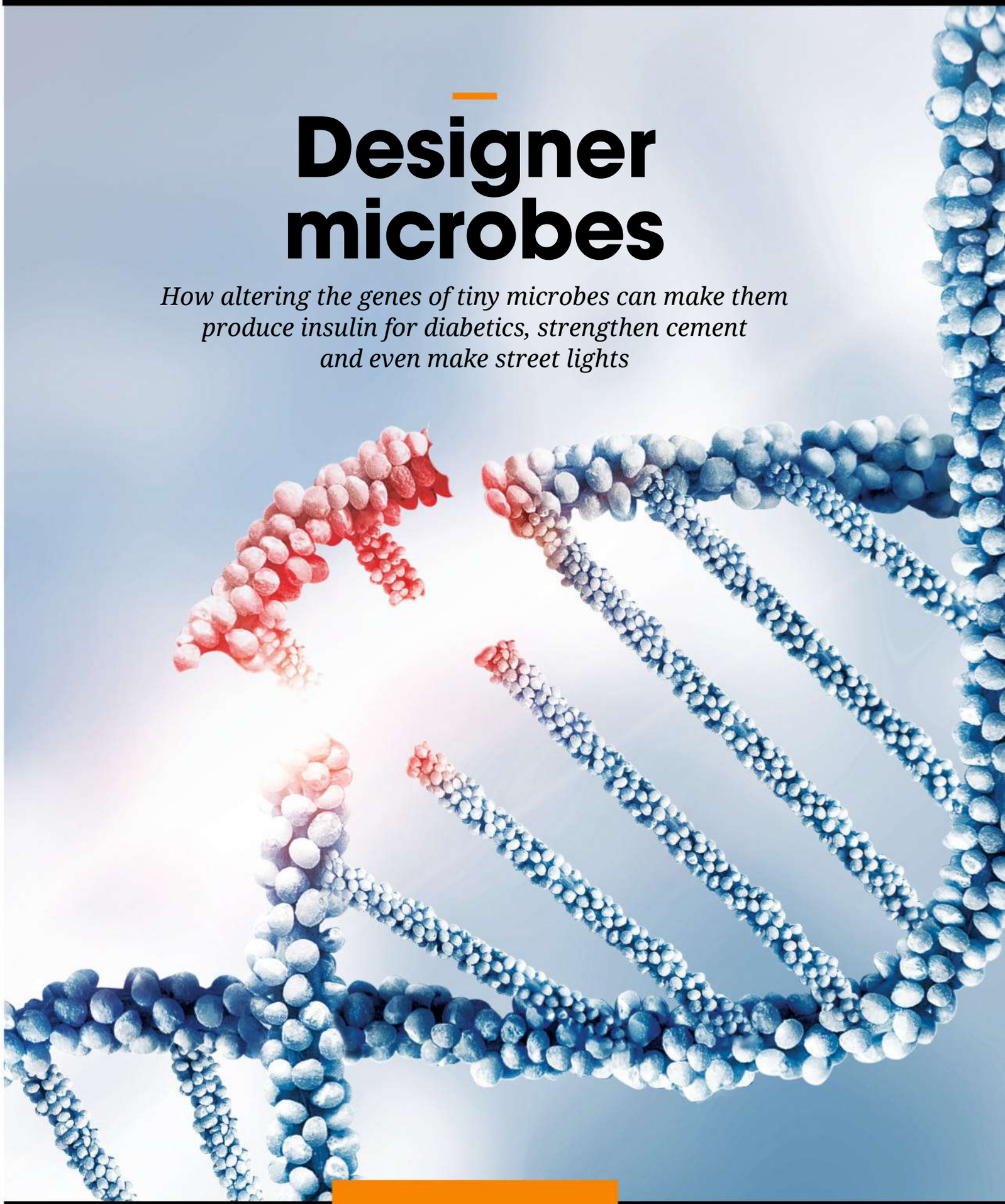
Genetic Science

Designer microbes

How altering the genes of tiny microbes can make them produce insulin for diabetics, strengthen cement and even make street lights



GENETIC SCIENCE

Microbes are extremely versatile microscopic organisms that include bacteria and viruses. Unseen by the naked eye, they conduct chemical conversions on a tiny scale, keeping the planet alive by recycling nutrients, both causing and preventing disease, but generally playing a vital role in our living planet. Some thrive in extreme environments, while others are carried with us at all times. There are 39 trillion microbial cells covering your body, maintaining your immune system and daily processes such as digestion.

As small organisms, microbes have simple genetic structures, making them easier for scientists to study. By gaining a more thorough understanding of what different sections of DNA control within a microbe, scientists can alter them to favour certain traits. These are genetically engineered microbes – dubbed 'designer microbes'. Microbes grow rapidly and multiply quickly. This enables desirable new genes to be mass-produced. In many projects involving modified microbes, DNA from other organisms – including human DNA – can be incorporated into that of a microbe, like bacteria. When these bacteria reproduce, over time large volumes of human genetic material are generated. This can be used to produce medical treatments for people whose own cells don't naturally produce enough of a specific biological compound in the body.

The possibilities for designer microbes are expanding, and today, research into their applications spans industries from medical and food to construction and textiles. Here are some of the most successful, inventive and futuristic applications of designer microbes.

Builder bacteria

Meet the bioengineered bacteria that have been called up for assistance in construction

Escherichia coli

Cement strengthener

E. coli can be modified to make more of the enzymes responsible for converting calcium and carbonate ions into calcium carbonate. E. coli in concrete strengthens the mixture, as the calcium carbonate fills any gaps.

Bacillus subtilis

Concrete self-healer

This releases spores into concrete. If dry concrete cracks, moisture is able to seep through and reach dormant spores so they can germinate, producing calcium carbonate crystals that seal the cracks.

Sporosarcina pasteurii

Biobrick insulator

S. pasteurii is genetically engineered to produce thermally insulating compounds. These fill gaps in concrete bricks, slowing heat loss from buildings.

Synechococcus elongatus

Building site decomposer

One application of this bacteria is for construction cleanup. It is engineered to improve its ability to degrade pollutants. For example, it can make proteins that bind to heavy metals at construction sites.

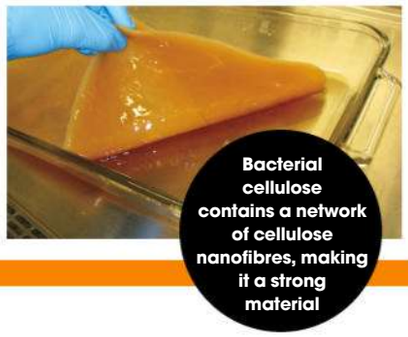
Myxococcus xanthus

Biofilm layer

This forms complex biofilms over surfaces but can be modified to improve its ability to cling to materials used in construction. The living layer makes materials more adhesive and helps prevent water damage by repelling water.

Self-dyeing leather

In an effort to make leather production more sustainable, scientists have modified bacteria to release a melanin-producing protein. This bacteria is Komagataeibacter rhaeticus, and after being genetically modified, it expresses the gene tyrosinase-related protein 1. This produces the pigment eumelanin, which is dark brown or black in colour. This bacteria naturally produces cellulose, and along with its modified genes, this cellulose is leather-coloured, making it an ideal replacement for the animal skin material. This bacterial species produces cellulose in strong, flexible and malleable sheets, ideal for textile purposes.



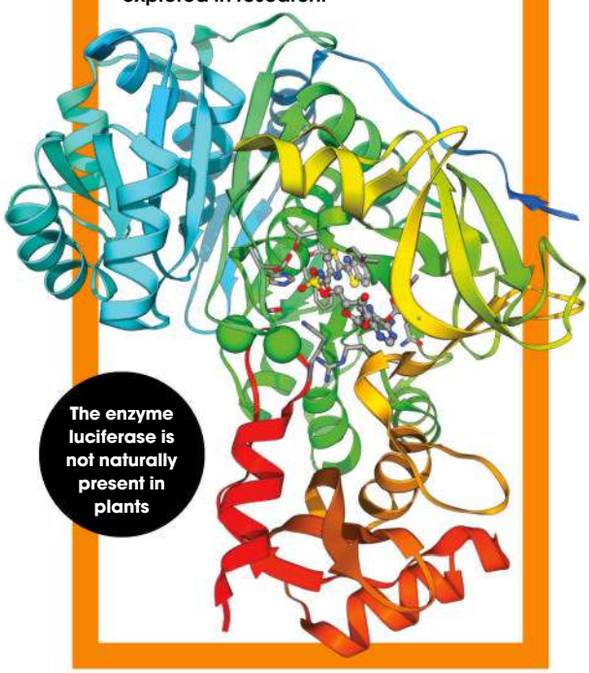
Bacterial cellulose contains a network of cellulose nanofibres, making it a strong material

© Shutterstock, © Wikimedia Commons/Lightenoughtotravel

Plant street lights

£88,500 ($114,300) is spent per year per mile of street lighting used in the UK. These lights are expensive and use electricity throughout the night. However, new techniques are being explored to harness the natural bioluminescent qualities found in nature to produce a more natural variation of the common street light. Bacteria that contain an enzyme called luciferase naturally illuminate when a biochemical reaction takes place. Luciferase works to oxidise the substrate luciferin in the organism – a reaction that requires oxygen and causes the substrate to glow. Bacteria that glow do so to help themselves be dispersed: they can usually survive in the digestive tracts of animals, so attracting animals to them helps them be ingested and relocated.

Scientists have demonstrated that the genes responsible for producing luciferase and luciferin can be cut from bioluminescent bacteria and inserted into the genes of evergreen plants. The genes of the bacteria can be modified to alter their metabolic processes and sensory cues so that they produce more light and are consistently glowing when darkness falls. The plants that these genes are inserted into need to be strong to reduce the chance of damage, and also evergreen so that their leaves glow all year round. Prunus lusitanica is one such tree species being explored in research.

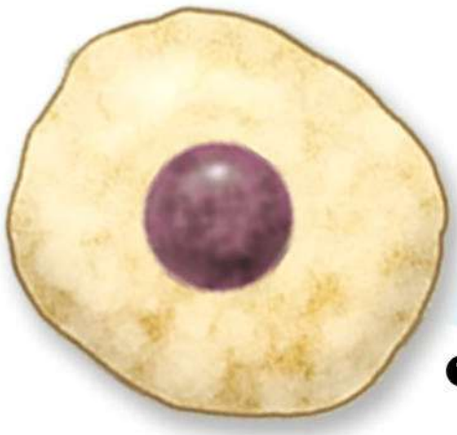


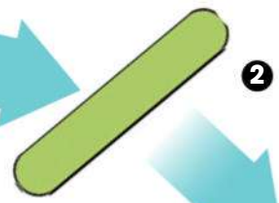
The enzyme luciferase is not naturally present in plants

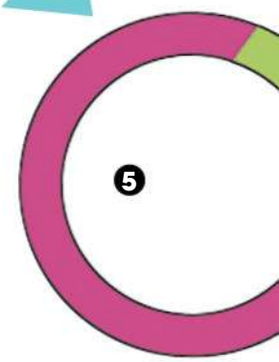
Making insulin for diabetics

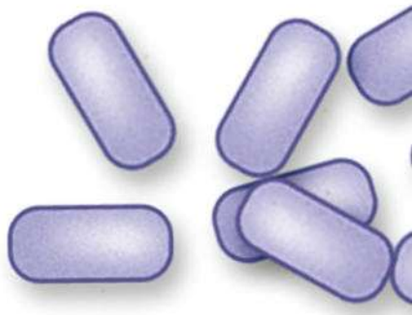
Inserting the human insulin gene into bacterial cells enables mass production of the hormone vital to regulating blood sugar

Did you know? 200 million people rely on insulin therapy









1 Human cell
The human cell has a single insulin gene on chromosome 11.

2 Isolated gene
The insulin gene is removed from the human cell.

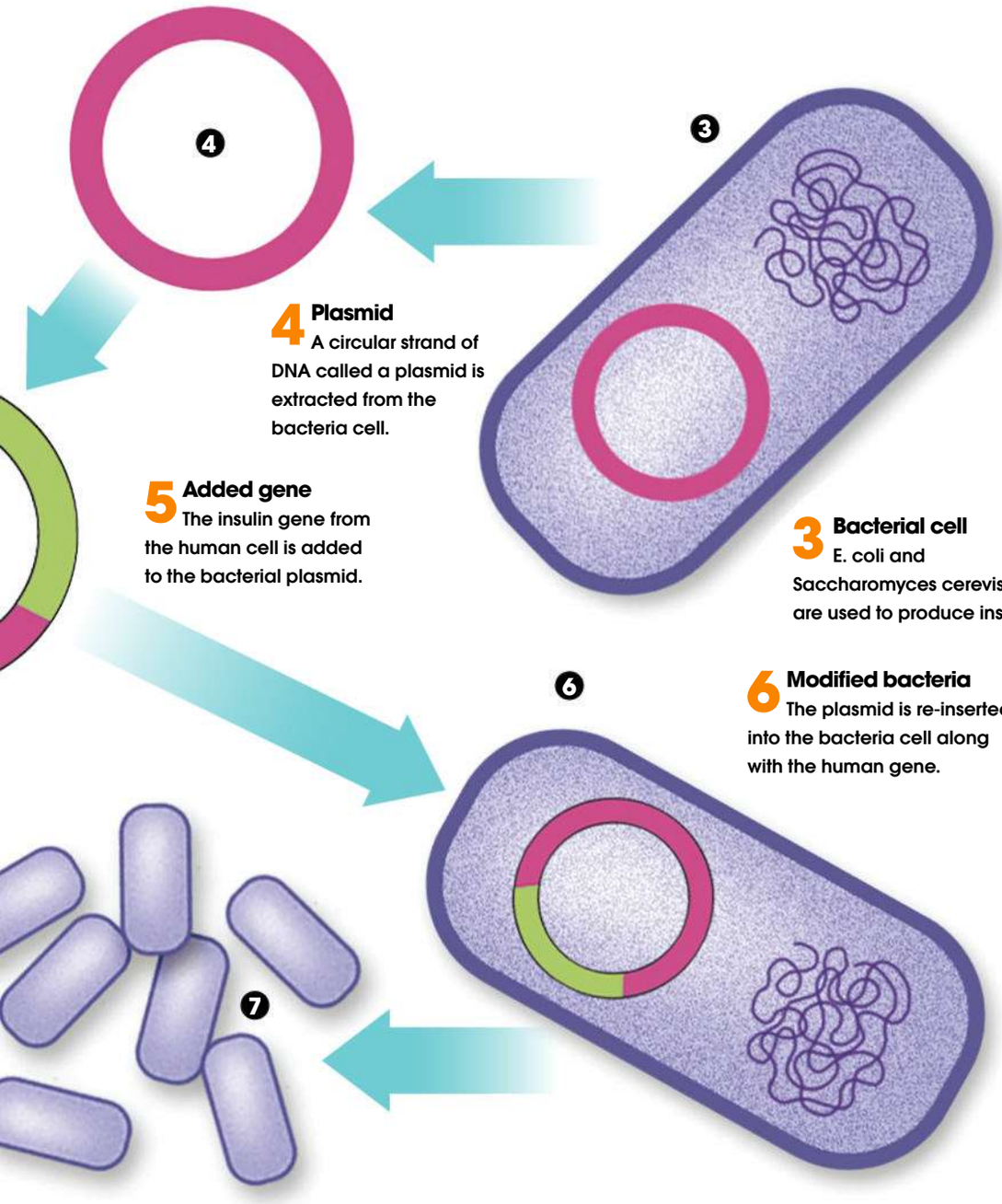
7 Multiplying cells
The bacteria cell splits in two and continues to multiply, accumulating identical insulin-producing cells.

8 Medicinal insulin
The human insulin is extracted from the bacteria cells and is treated, ready to be supplied to diabetes patients.

Oil-spill eaters

Around 9 million tonnes of oil enter the world's oceans each year, polluting marine environments. Many of the spills come from drilling rigs, tankers, storage facilities and pipelines. The main pollutants in these spills are hydrocarbons – compounds that contain hydrogen and carbon. Hydrocarbons remain in the water for many years, killing wildlife with their toxic chemicals and sinking to the seafloor to contaminate sediment. In addition, they are poisonous to humans. The minute microbe facing the mighty cleanup task in polluted seas is called Pseudomonas putida. The bacteria's plasmids are genetically modified to alter their metabolism, allowing them to break down and feed on the masses of complex hydrocarbons tainting the seas.

In US waters, there are over 150 oil spills a year



4 Plasmid
A circular strand of DNA called a plasmid is extracted from the bacteria cell.

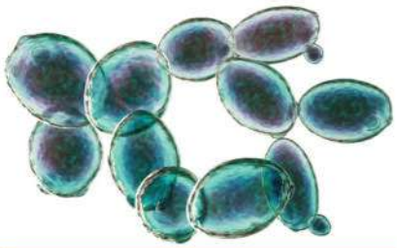
5 Added gene
The insulin gene from the human cell is added to the bacterial plasmid.

3 Bacterial cell
E. coli and Saccharomyces cerevisiae are used to produce insulin.

6 Modified bacteria
The plasmid is re-inserted into the bacteria cell along with the human gene.

Boosting biofuel

How editing yeast produces ethanol for an eco-friendly alternative at the fuel pump



1 Engineering yeast
During fermentation, yeast converts the sugar from food waste into ethanol. This yeast is genetically modified to increase its tolerance to the ethanol it produces.

2 Fermenting fuel
The enzymes in the yeast convert glucose into ethanol, carbon dioxide and water. This process requires controlled conditions, with no oxygen present and warm temperatures of 25 to 35 degrees Celsius.

3 Ethanol extraction
The ethanol is extracted from the bioreactor to be added to gasoline fuels. Because the yeast was modified, higher concentrations of ethanol can be produced before the yeast stops working.

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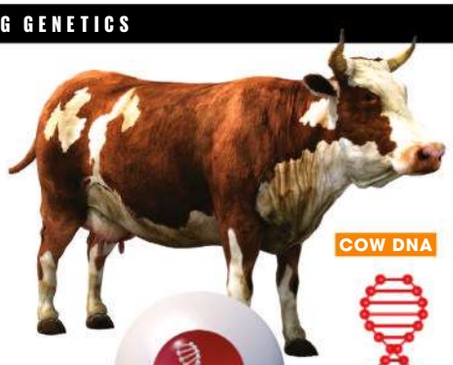
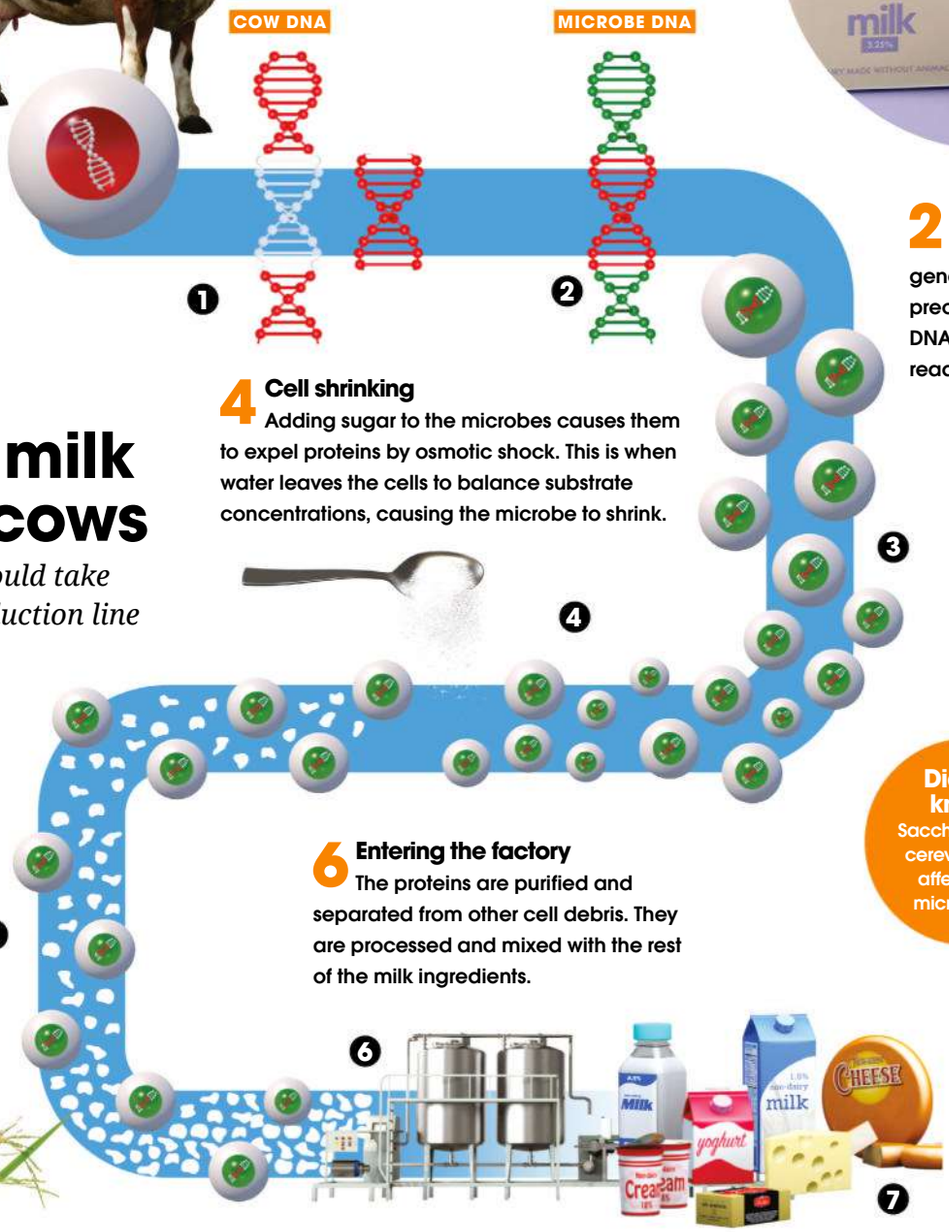
Making milk without cows

How microbes could take over the dairy production line



Cow-free dairy company Opalia is already able to produce milk without input from any animal

© OPALIA



1 Cow DNA extraction
The genes responsible for producing dairy proteins and other milk components are isolated from a dairy cow's DNA.

2 Modifying microbes
The milk-producing genes are inserted precisely into microbial DNA so that the host can read the new instructions.

3 Microbe multiplication
The microbes reproduce. Each one is copied to contain the DNA instructions for making dairy proteins.

4 Cell shrinking
Adding sugar to the microbes causes them to expel proteins by osmotic shock. This is when water leaves the cells to balance substrate concentrations, causing the microbe to shrink.

5 Protein collection
As a stress response to shrinkage, the microbe releases its contents, including the dairy proteins.

6 Entering the factory
The proteins are purified and separated from other cell debris. They are processed and mixed with the rest of the milk ingredients.

7 Finished products
The resulting dairy products have the same taste, texture and nutrients as those in cow's milk.

Did you know?
Saccharomyces cerevisiae isn't affected by microgravity

There are billions of microbes in a rice plant's microbiome

© Adrian Mann

Pioneering engineering

For the first time, research published at the beginning of 2024 shows that scientists have engineered the microbiome of a plant. The microbiome of an organism is the community of microbes covering it. In a plant, this protects it from disease and influences the nutrients available to it. When modifying a rice plant's microbiome, scientists increased the population of beneficial bacteria by editing one gene. Plants with this healthy new microbiome are less reliant on pesticides that are damaging to the environment. Within a complex molecule of the plant's cell walls, called lignin, the team of scientists found one gene that directly influences the microbiome. When they overexpressed the gene, the result was an influx of these beneficial microbes.

Reducing beer bitterness

One of the processes in which genetically modified microbes are used to influence a product's taste is beer fermentation. Yeast is used to ferment sugars and turn them into alcohol for beverages. However, the extra roles of these microbes can be controlled by changing their genes. As well as providing the alcohol content, yeast can be modified to express different enzymes depending on their roles. Some of the enzymes made by yeast break down bitter compounds in beer. Overexpressing the genes responsible for this enzyme's production will increase the number released into the beer batch, making a milder tang and creating new flavour profiles.

Yeast content influences a beer's taste and aroma

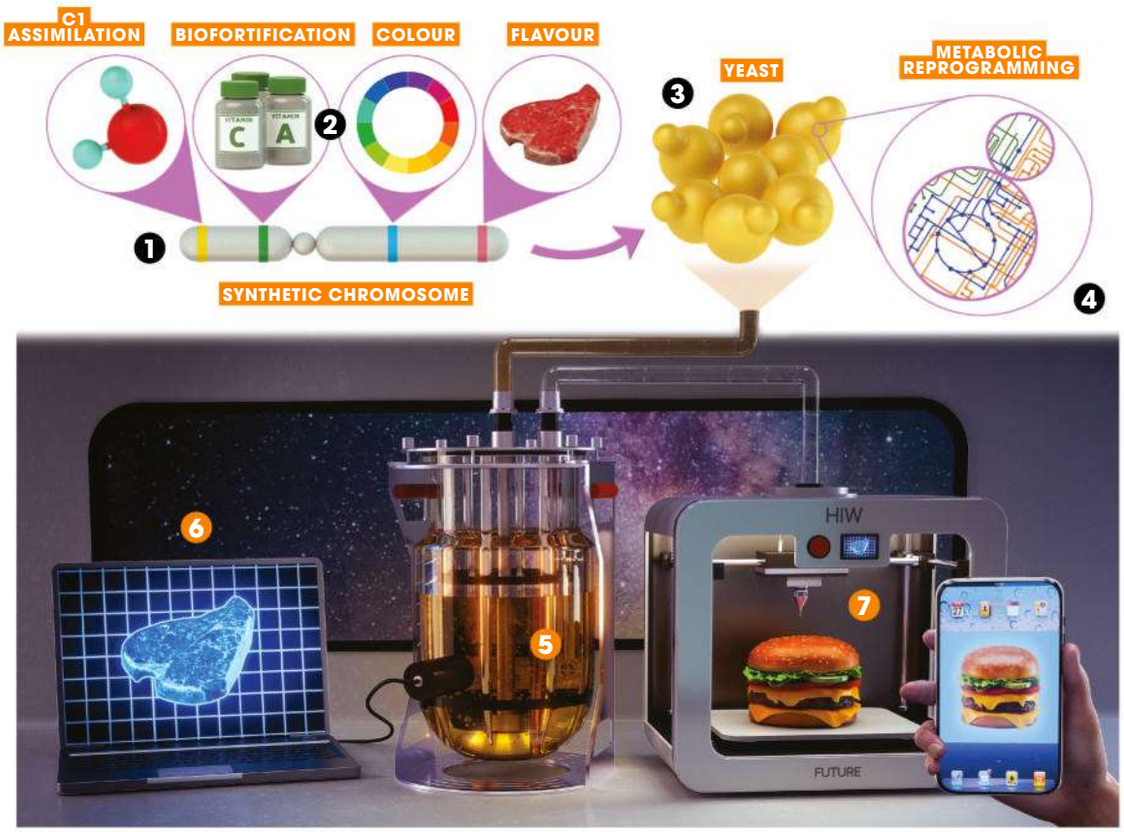
3D-printed meals

NASA is working on ways astronauts could make a range of nutritional foods in space from yeast

1 Synthetic chromosome
A synthetic chromosome is built from natural components that can be inserted into a cell. In this case, the genes contain instructions to produce a specific food's traits.

2 Sensory attributes
Some of the genes that need modifying include those responsible for carbon assimilation, nutrient production, colour and flavour. Carbon assimilation ensures that compounds with a single carbon atom can be used by the yeast for its growth so waste gases in space can be used up.

3 Yeast
The new traits then need to be genetically engineered into Saccharomyces cerevisiae. Yeast is already edible and can double its biomass in 90 minutes.



© Nicholas Forder

4 Metabolic reprogramming
The yeast has to be reprogrammed so that it can express appropriate traits from its genes.

5 Intelligent bioreactor
The yeast is stored in a bioreactor, which tweaks how traits such as colour and nutrients are expressed in the yeast for each food.

6 Food vision
Data about the desired food is communicated to the bioreactor.

7 3D-printed product
Food compounds produced by the yeast are pumped out of the bioreactor in a liquid-like 'food ink' to be precisely printed onto a tray in the shape of well-known foods. In layers of varied composition, more complex foods can be recreated.

5 Facts roles of designer probiotics

1 Digestive aid
The probiotic Lactobacillus acidophilus can be genetically modified to produce the enzyme lactase. The enzyme helps break down lactose into glucose and galactose in lactose-intolerant people.

2 Allergy targeting
When Bifidobacterium bifidum is edited, the probiotic makes anti-inflammatory proteins called cytokines that prevent allergic reactions.

3 Immune support
Lactobacillus rhamnosus can be genetically engineered to produce beta-defensin 2, a protective molecule that assists the body in fighting germs.

4 Reducing inflammation
The gut microbe Faecalibacterium prausnitzii can be modified to increase the production of anti-inflammatory fatty acids in the gut.

5 Vitamin production
When its genes are edited, Lactobacillus reuteri produces vitamin B12 in the gut, an essential vitamin for red blood cell production and nerve health.

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How cloning animals works

When Dolly the cloned sheep was born so was a new era of biological research

GENETIC SCIENCE

She was born into the world like any other sheep – tiny, fluffy and bleating. But Dolly wasn't the same as any other sheep. Or rather, her uniqueness was that she was like just one other sheep. In fact, she was identical to one other sheep. Dolly was a clone.

Clones are organisms, or cells, that are genetically identical to their parent, and they have existed in nature for millions of years. Single-celled organisms and plants can produce genetically identical offspring and natural clones, for example, identical twins, occur in humans and other mammals. These natural clones have almost identical DNA. However, animal cloning has been experimented with for over 100 years, starting with more basic animals like salamanders and working up to complex mammals like sheep and cows.

Double trouble: cloning methods

There are two main methods of cloning animals: somatic cell nuclear transfer (SCNT) and embryo splitting. It was the SCNT method that was used to produce Dolly the sheep. Both methods are forms of 'reproductive cloning', a type of artificial cloning of which gene cloning and therapeutic cloning are also a part of.

Reproductive cloning

SCNT cloning starts with finding a suitable nucleus donor. These can be obtained directly from the animal or they can be grown in a laboratory. They are usually skin cells, which have a relatively long lifespan and can tolerate being frozen. The other cell that needs to be obtained for the cloning procedure is an egg cell. The egg cell is enucleated – a process that involves sucking out the nucleus by using a tiny needle. When the cell has been enucleated there is no DNA left behind, but it remains filled with cytoplasm. The nucleus donor cell is enucleated in the same way, but instead of being discarded, the lone nucleus is injected into the egg cell. An electric shock is applied, which triggers it to start dividing. If everything goes well the embryo is implanted into a surrogate. The cells divide normally, and a few months later, a healthy clone is born. So far, there is no evidence that the process is at all detrimental to the clone. Dolly was able to reproduce and had healthy offspring, which suggests her fertility was not impacted by the way she came into life.

Therapeutic cloning

Therapeutic cloning uses the same methods right up until the point of electric shock. The donor cell, however, belongs to a cell from a patient who needs stem cells. After the fused cells have divided several times, they becomes a pre-embryo ball of cells known as a blastocyst. A blastocyst has an outer and inner layer, and within the inner layer are the prized stem cells. While most cells are specialised to a specific job (i.e. neuron, muscle cell etc.) stem cells have the potential to develop into any cell type. The harvested stem cells are infused into a patient and, under the right conditions, start functioning where needed.

"Animal cloning has been experimented with for over 100 years, starting with more basic animals like salamanders"

Did you know? Individual genes can also be cloned so that scientists can research them

Two cloned beagles, Magic and Stem, were born at the National Seoul University in January 2009 in Seoul, South Korea

Achievements in cloning history

The breakthrough moments in scientific history that advanced the field of cloning

1938 Hans Spemann proposes a "fantastical experiment" to transfer one cell's nucleus into an egg without a nucleus, the basic method that would eventually be used in cloning.

1952 Robert Briggs and Thomas King successfully transfer the nucleus from an early tadpole embryo into an enucleated frog egg.

1984 Steen Willadsen clones a sheep from an embryonic cell in a technique known as nuclear transfer.

1996 Dolly the sheep – the first mammal to be cloned from an adult body cell – is born in Scotland.

2001 Two animals – a mouflon sheep and a gaur (Indian bison) – are cloned as part of an effort to save these species.

2003 Researchers successfully clone the first extinct animal, a Spanish mountain goat called the bucardo, but the clone died minutes after it was born.

2013 Human embryos are cloned for the first time to produce embryonic stem cells with the hope they may go on to treat diseases.

© Getty

Dolly is possibly the world's most famous clone

The life of Dolly the sheep

Dolly was born on 5 July 1996 at The Roslin Institute in Scotland. Her birth was a result of an experiment to develop genetically modified livestock. She had three mothers: a Finn-Dorset provided the DNA, a Scottish Blackface provided the egg and a third, a Scottish Blackface, was impregnated with the embryo. 148 days later, the surrogate ewe gave birth to Dolly. She was the sole surviving adult from 277 cloning attempts.

Dolly went on to have six healthy lambs, all conceived naturally. She died at the age of six from a disease unrelated to her being a clone, but her life encouraged scientists to continue experiments with other animals. Since then, pigs, cats, dogs cows, horses and camels have been cloned successfully.

The Seoul National University and RNL Bio Company offers clients a service to clone their dead pets

Embryo splitting

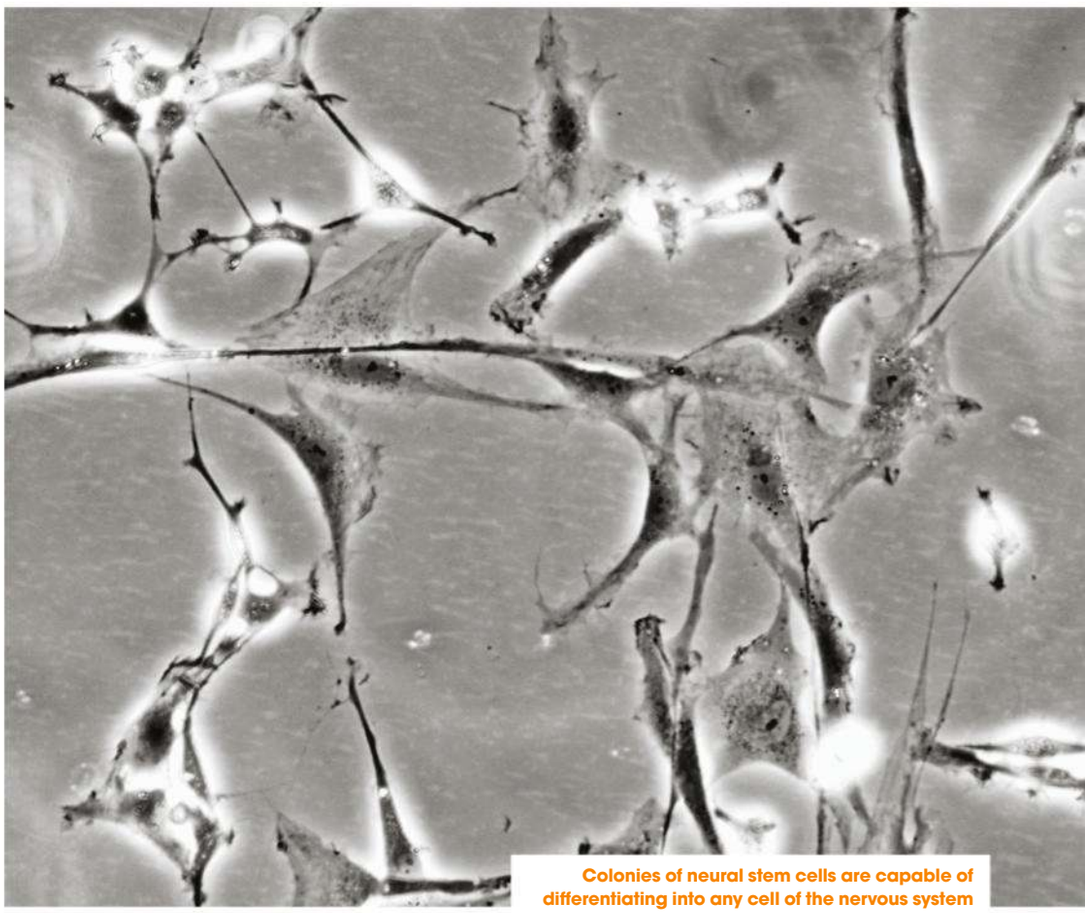
The simplest form of artificial cloning, this method begins with the formation of a zygote. This zygote divides and eventually, the embryonic cells can be separated. Each separated cell continues growing and can be implanted into a surrogate. The implanted cells are identical as they were originally formed from the same embryo. This process is similar to that of the development of identical twins but has limited potential.

Can we clone humans?

Undoubtedly, cloning is a powerful biological technology. Scientists have been able to use the technique to breed endangered species and resurrect extinct animals. There has even been talk of bringing back the woolly mammoth after the discovery of preserved soft-tissue remains of these prehistoric giants. Yet, while laboratories are researching and developing therapeutic cloning using human tissue, there have been no actual human clones created to date. This is partly due to the ethical problem of bringing cloned individuals into existence without fully knowing if the method is safe or what the impact might be on the cloned human's life. Other concerns include the fact that reproductive cloning could be prone to wide-scale abuse, such as cloned humans being used for organ and tissue harvesting.

What's the point?

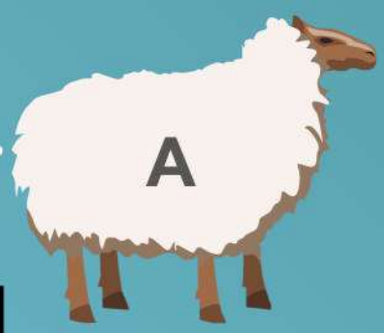
Cloning is expensive, time-consuming and has a very low success rate. However, developing these methods has been vital to our understanding of human developmental biology and has provided new treatment options in medicine. It is hoped that soon patients with an organ disease or failure will no longer have to risk their body rejecting their new transplant. Instead, they will be able to replace the organ with one that is genetically identical but without the wear and tear. It won't be long until we see scientists growing new livers for patients with liver disease, new hearts for transplants and even new brain neurons for people suffering from brain injuries – all perfectly genetically identical to the patient.



Colonies of neural stem cells are capable of differentiating into any cell of the nervous system

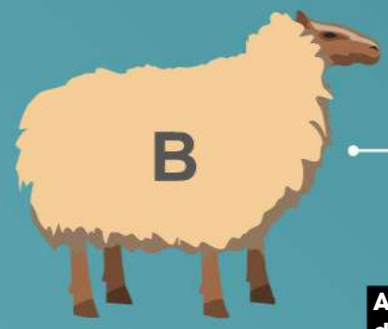
How does cloning work?

The incredible process behind creating genetically identical organisms



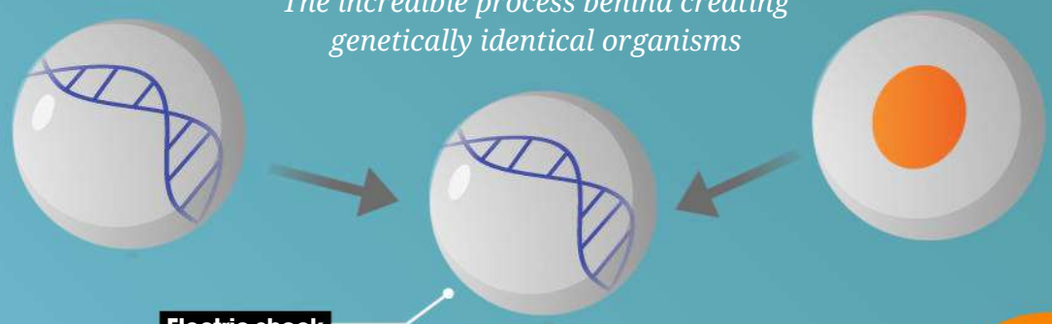
Donor mammary cells

A donor cell has its nucleus removed and the rest of the cell is discarded.



Adult donor cells

An enucleated egg cell from another donor is injected with the extracted nucleus.



Electric shock

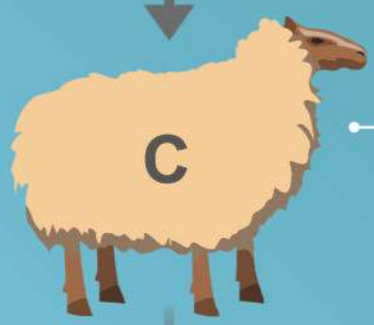
The cells are fused together and stimulated to divide using an electric shock.

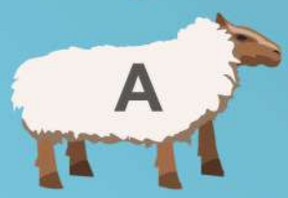
Fused cell

The cell divides, gets larger and becomes an embryo. The embryo contains the same genetic information as the adult mammary cell.

Implantation

The embryo is inserted into the uterus of a surrogate mother.





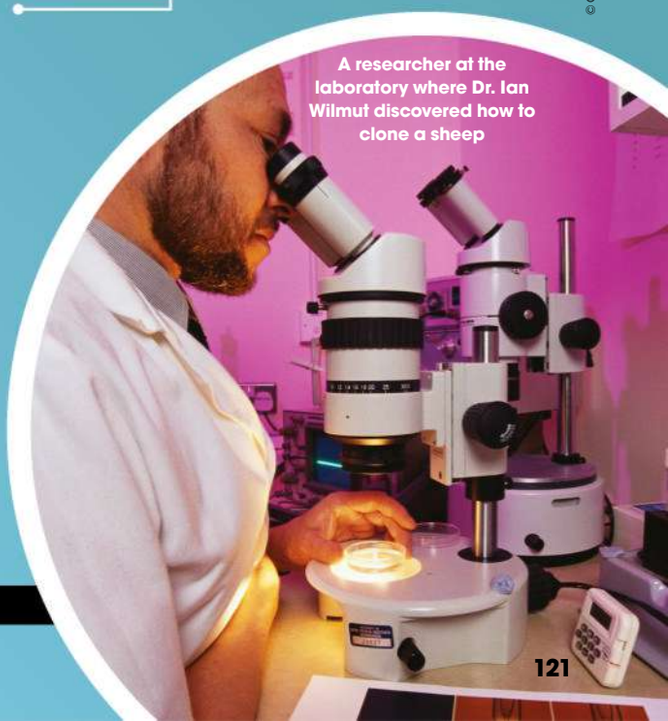
Clone is born

The embryo develops normally and is born.

Did you know?

South Korea's Incheon Airport uses several dogs all genetically identical to Chase – a top drug-detection dog

> "It won't be long until we see scientists growing new livers for patients with liver disease"



A researcher at the laboratory where Dr. Ian Wilmut discovered how to clone a sheep

© Getty

The problems with human cloning

What's stopping scientists from creating lab-grown people?

What if there were two of you? You could finish your chores and errands in half the time, juggle those overlapping social engagements or let one of you work while the other takes a mini vacation. In theory, the idea of cloning ourselves might seem like a no-brainer, but in actuality, creating human clones is rife with brain-stretching scientific and moral obstacles.

Since the creation of Dolly the sheep, the first cloned mammal, the last 20 years have been filled with many examples of DNA being taken from different species of animals, such as rabbits, rats, dogs and horses, and successfully creating a copy. Although the science works for those species, it's not a one-size-fits-all technique.

One of the main challenges in human reproductive cloning is replicating our life span. The genetic information that is used as the instruction manual for cloning comes from the nucleus in an adult cell. As adult cells grow and divide, over time the end portions of our chromosomes, known as telomeres, shorten a little with each division. By the time we reach adulthood, chromosome telomeres are quite short, so after implanting adult chromosomes into an embryonic egg, the chromosomes shorten beyond the normal amount. This shortening would lead to clones developing life-threatening conditions and typically halving their life span when compared to their DNA donors, as seen in animal studies. Other biological hurdles occur during the process of extracting the nucleus from the donor egg. For example, during removal, vital proteins within the cell that are important for cell division can also be unwittingly removed.

Human cloning is also an ethical minefield. Would human clones be deemed sub-human? Is bringing the DNA of a deceased loved one back to life the right thing to do? Along with the scientific obstacles of human cloning, the dilemmas it poses are challenging to overcome. As it currently stands, we are not technologically advanced nor morally prepared enough to bring biological doppelgängers into the world.

Are they among us?

Could it be possible that there is a human clone among us? Back in 2002, biotech company Clonaid claimed to have achieved the work of science fiction and birthed the world's first cloned baby, later known as 'Eve'. Following sweeping newspaper headlines, public interest mounted about the real-life possibilities of human cloning. However, something didn't add up about Clonaid's medical revelation. Clonaid had supposedly taken the DNA from the donor 'mother' to be implanted into the DNA-vacant egg and reimplanted into the donor, resulting in a successful pregnancy. What Clonaid didn't provide, however, was any medical or photographic evidence of Eve for peer review, leaving both the media, scientists and the public with no way of knowing for sure their claim was true, although it was generally concluded to be false.

The road to human cloning

Discover the milestones science has made in cloning technology

1952
Scientists showed they could remove the nucleus of an embryonic frog cell and transfer it to an enucleated egg cell.

1963
The first cloned fish, a carp, is created from a DNA transfer by Chinese scientists.

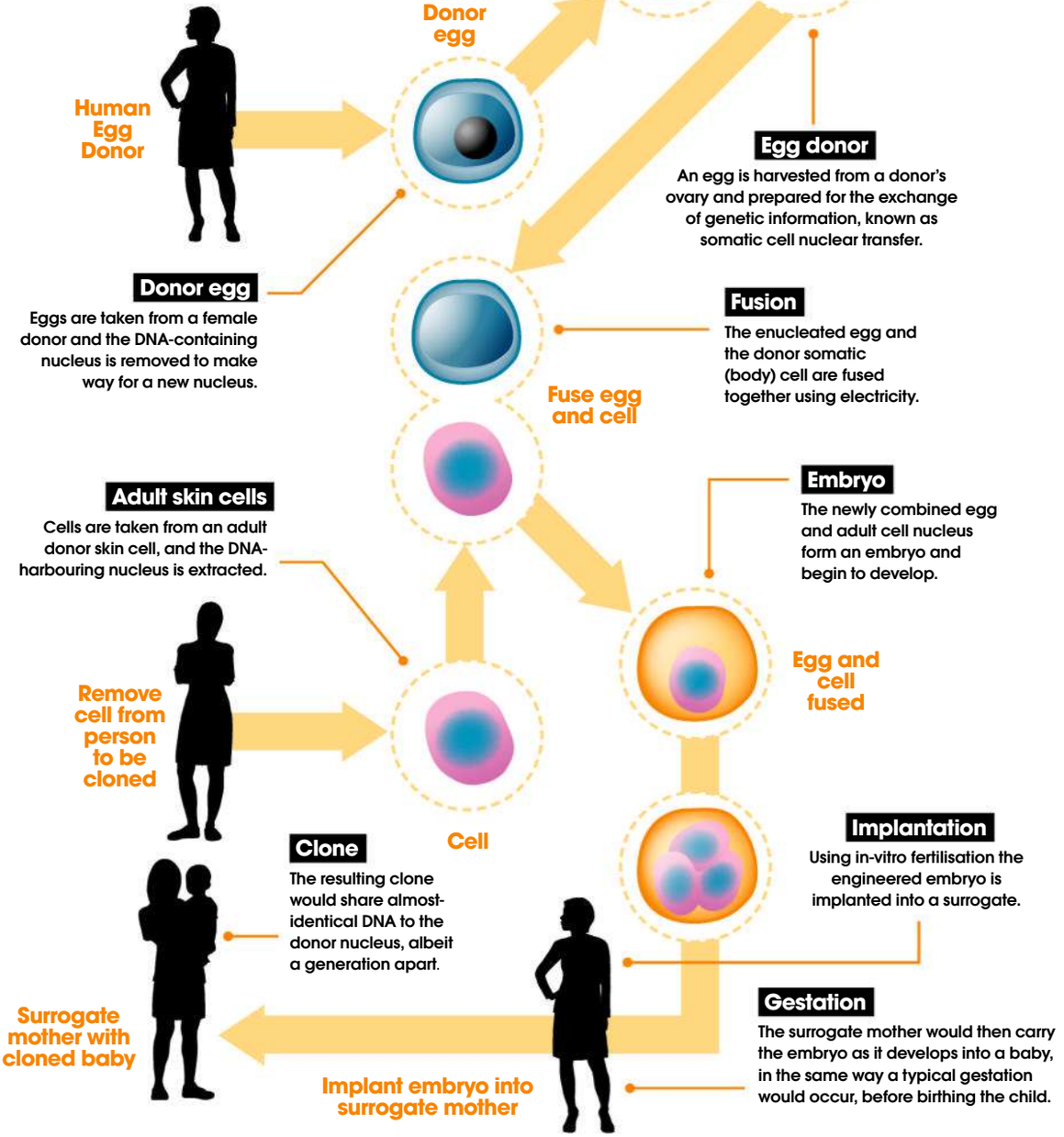
1996
Dolly the sheep is born, the first mammal to be cloned from an adult cell.

1998
50 mice are reportedly cloned from a single mouse over several generations.

2001
Cats are added to the list of cloned animals when American scientists created 'CC'. However, she differed physically from her 'mother'.

Human cloning

The science behind creating our biological doppelgängers



All of these macaque monkeys are almost genetically identical, included those artificially edited by scientists

2017

Going ape for cloning

One of the proposed benefits of cloning is the ability to assist in the treatment of human conditions such as Alzheimer's disease and cystic fibrosis. A couple of years ago, Chinese scientists made a huge advance in the potential of cloning when they created Zhong Zhong and Hua Hua, two macaque monkeys. Using the same method of somatic cell nuclear transfer used in the creation of Dolly the sheep back in 1996, genetic information from an adult cell was transferred into an enucleated egg and implanted into a surrogate.

Why this is a potential game changer for the science of cloning is down to the comparable higher cognitive functions monkeys share with humans. Having achieved success in cloning, researchers at the Institute of Neuroscience in Shanghai have now used the technique to clone another macaque monkey which had been genetically modified to disable a gene crucial for sleep. The resulting five clones were found to share the edited mutation and thus developed the same sleep disruption, therefore shedding light on the role of gene expression and disease development.

2001
A six-cell cloned human embryo is produced to harvest the developing stem cells.

2002
The first cloned rat, 'Ralph', is born. From 129 implanted embryos, only three pups were born.

February 2003
Dolly is euthanised after developing a lung disease at just 6.5 years old – half the age of a naturally born sheep.

2005
The world's first cloned dog named Snuppy, an Afghan hound, is born in South Korea.

2013
Human skin cells are reprogrammed into their original embryonic state in America.

2014
Scientists placed an adult human skin cell nucleus into the enucleated egg and began to start embryonic development.

© Getty

Genetically modified organisms

How and why do scientists manipulate genetic information?

To create a GMO, scientists must first decide what trait to introduce into an organism, such as resistance to drought or the ability to produce a particular vitamin. By analysing the genetic code, they can identify exactly which part of the DNA codes for the gene of interest and select enzymes that will cut out the part they need.

Generally, they will then alter the genome of a plant by using a bacterium called Agrobacterium tumefaciens, which naturally enters plants' cells in the wild. A few specific genes are then removed from the bacterial plasmid, a circular genetic structure that can replicate independently and be transmitted across bacteria. This cutting leaves a linear piece of DNA that codes just for replication instructions and for basic cell function.

To create the new 'recombinant plasmid', the cut gene of interest, the linear receiving DNA, and the enzyme DNA ligase are all combined, causing the integration of the new gene. The cells are grown in culture and will produce seeds as adults, which will all inherit the implanted transgene, though they may not express it.

Background

Organisms' genomes contain the blueprints for how they work, and genetic modification is the transfer of some of this information from one organism to another. Nature has done this for millennia; for example, some types of sweet potato express a gene from bacteria that introduced itself into the potato genome.

Scientists then developed a way to do this intentionally. The first patent for a genetically engineered organism was a bacterium. Developed in 1971 by Ananda Chakrabarty, an Indian-American biologist, it was designed to have a taste for crude oil so that it could be used to help clear oil spills by either absorbing the oil or breaking it up.

How we can use GMOs

GMOs have the potential to reduce world hunger and malnourishment, particularly for those living in low-income countries. Examples of such innovations include 'golden rice', which is being modified to have an enhanced level of the much-needed vitamin beta-carotene.

Other types of rice have been modified so that they can survive with very limited water after having a gene from a desert plant introduced into its genome. Tomatoes that are resistant to frost and freezing temperatures have also been made using an anti-freeze gene from a cold-water fish. In the future, we could even see the introduction of vaccines and medicine in some foods, like the potato which has been engineered to produce an edible vaccine against pathogenic E coli.

Making a GMO

How scientists use genetic engineering to give plants new characteristics

Step 1
First, the plasmid is removed by opening up the bacterial cell and purifying the contents inside.

Step 2
T-DNA is cut from the plasmid using restriction enzymes, which slice the genome at specific points to remove some genes.

Step 3
The foreign DNA that needs to be transferred into the T-DNA is also cut using restriction enzymes to select the target gene.

Step 4
The cutting process creates a linear molecule that is ready to accept new DNA.

Step 5
The gene and opened vector are mixed together with DNA ligase, an enzyme that connects the ends of the gene and open vector.

Step 6
Heating up the cells (heat shocking) is thought to create pores that allow the engineered plasmid to enter the plant cell.

Step 7
The bacterium carries the gene of interest and the replication instructions into the chromosomes of a plant cell wall.

Step 8
The plant cells grow in culture and eventually produce seeds that contain the naturally inherited transgene.

Genetically modified 'golden rice' contains more beta-carotene than standard rice

"Scientists decide what trait they would like to introduce, such as resistance to drought"

Summary

GMOs are created using gene manipulation technology. By inserting a foreign gene into a new host, scientists can produce an organism that expresses a trait it wouldn't usually have in nature.

© Illustration by Jo Snodgra

How is food genetically modified?

Explore the production of human-made food perfection that takes place in science labs

The majority of what we eat has been sourced from farms and factories which breed and produce especially for the food industry. For centuries, humans have been manipulating the outcome and appeal of food sources by changing traits. Selecting the ideal features, people have systematically created many combinations of favourable features in food that would not naturally have occurred.

Genetic modification is one way of ensuring our food has the desired outcome, in a precise and scientific procedure. Previous selective breeding methods relied on luck in some parts of the process, but for this more advanced technique, an organism's DNA structure is cut and modified in a more direct act. This closely controls the outcome and standard of produce.

In order to grow food that is best suited to its environment while incorporating the best traits, scientists look to naturally thriving organisms. Taking the advantageous aspects of their DNA, these are incorporated into mass food production and the creation of crop perfection. Experimenting with new varieties, genetically engineered foods can increase flavour and nutrition, while also protecting the organism against disease. Created in laboratories, scientists play with the combinations of genes in various food sources for an end result that is superior to natural qualities.

But are there any negative impacts of food produced in this way? Over the years, many have raised concerns over whether the growth and consumption of these foods is bad for our health and that of the environment. Altering nature's course can introduce beneficial aspects to each food source, but it is also important to acknowledge where the method could have downfalls. Some believe modified foods could increase the likelihood of allergic reactions in those who eat them, as well as justify the creation of more toxic herbicides and pesticides by chemical companies to be used on resistant crops.

Future food

Beginning only as a way to enhance the value of plants, genetic modification is now being explored within the animal food industry. The first animal genetically edited for food quality was salmon. These fish were modified in Canada to adopt the ability to reach full size in only 18 months - half the time it would usually take.

The next steps in genetic modification could be more radical. Pigs and chickens are being worked on to create disease-resistant animals alongside dairy cows without horns and sheep with the ability to produce more offspring.

In terms of crops, being able to grow food that is resistant to harsh environments may be a saviour in preventing famine. Some areas struggle with an extreme lack of rainfall, suffering from droughts that hinder their ability to provide food. With climate change likely to exacerbate these conditions, scientists are experimenting with the development of drought-tolerant crops in preparation.

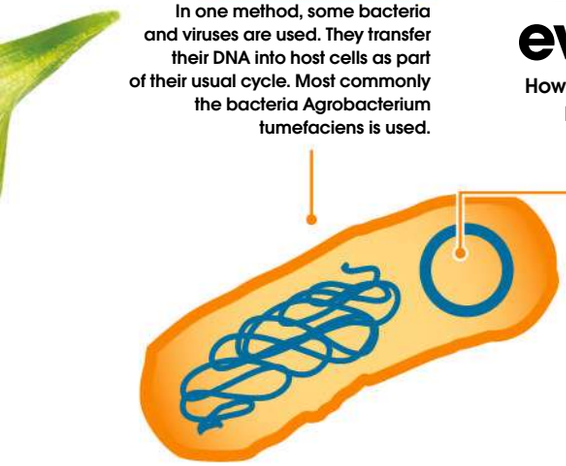
© Juryelsory/Flickr

A gene gun is used to alter the DNA of corn cells

Crops such as wheat and soybeans could be engineered to close pores where water is lost

Forced evolution

How favourable genes are passed into plants

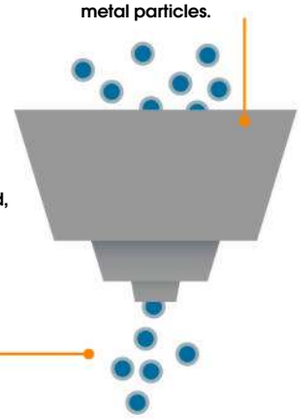


Beneficial bacteria

In one method, some bacteria and viruses are used. They transfer their DNA into host cells as part of their usual cycle. Most commonly the bacteria Agrobacterium tumefaciens is used.

Gene transferral

The desired gene is put into the bacterial cell. To ensure it is accepted, bacteria are shocked with either electricity or heat.

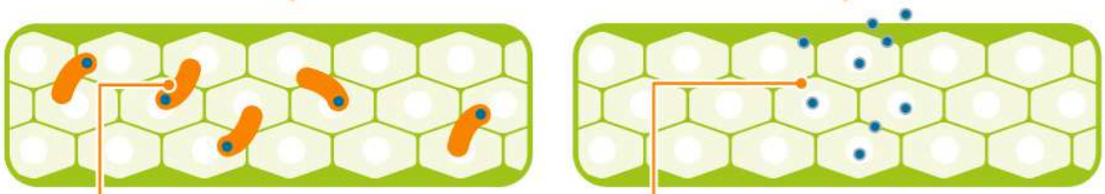


Gun precision

Gene guns are often used to alter plant genomes. These precise guns are filled with DNA-coated metal particles.

Dense bullets

Metal is used to increase the density and allow particles to penetrate plant cells. Using metal means that less DNA needs to be used in each shot – only a thin coating.

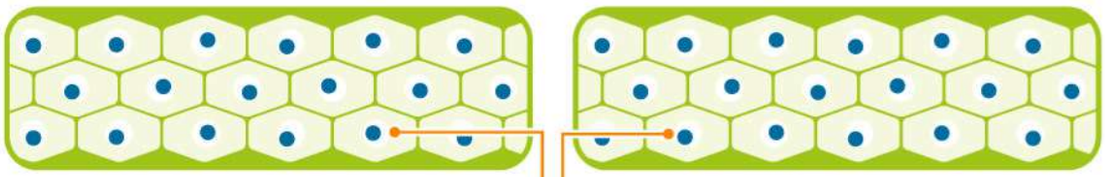


Entering the plant

The bacteria take their newly acquired genes into the plants' cells.

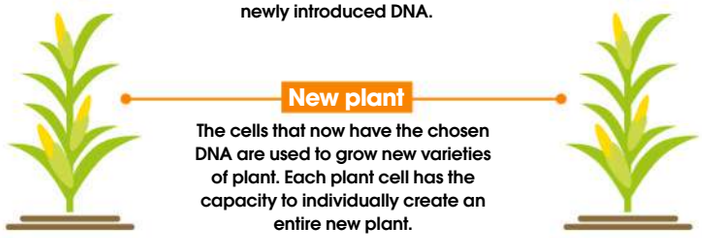
Forceful firing

The particles bombard the plant cells as they are fired into the tissue. Any cells that have been successfully targeted now have the genetic trait incorporated within their DNA.



Embedded genes

Some of the plants' cells successfully take up the newly introduced DNA.



New plant

The cells that now have the chosen DNA are used to grow new varieties of plant. Each plant cell has the capacity to individually create an entire new plant.

Use of the toxic herbicide glyphosate has increased by 1,500% since resistant GM crops were introduced

5 Facts Fictitious fruits becoming reality

1 Arctic apple
Created to resist turning brown, these apples are available in the US. Once the apple is cut, the inside is prevented from changing colour. Those responsible for modifying the apples claim that foods with these qualities will help to reduce food waste.

2 Peachy strawberries
Strawberries are being experimented with in order to give them the sweetest taste possible. In a merger between two fruits, some modification is producing strawberries that are peach flavoured.

3 Disease-resistant bananas
A common disease in bananas called fusarium wilt has prompted scientists to develop a batch of resistant bananas. This will ensure that these bananas can all stay healthy for consumption.

4 Spicy tomatoes
Some Brazilian scientists are testing the possibility of hot tomatoes with their spicy selection. Tomatoes have some of the same genes which produce spicy chemicals as chillies, but they are dormant. Altering this part of the genome, tomatoes could be used as more accessible chillies.

5 Rainbow papaya
The rainbow papaya was modified to make papaya production more efficient. Papaya farms across Hawaii were suffering from a loss of a huge number of their fruit to the ringspot disease. Since commercialisation in 1998, the rainbow papaya is claimed to have saved the industry in Hawaii.

© Getty

Genetic intervention

How altering a crop's genes can arm plants for insect warfare

Genetically modified (GM) plants have been produced since the early 1980s, with the first run of GM tomatoes hitting the shelves in 1994 in the US. In a nutshell, GM foods have been genetically modified by inserting a new chain of genetic information that plays a particular function from one organism to another. Scientists take the natural pest control abilities or disease resistance of one plant and put the part of the DNA that provides that ability into another plant.

Selecting desirable genetic traits in food products has existed for thousands of years. During the mid-1800s, Austrian scientist Gregor Mendel discovered that, through selective breeding, he could breed different generations to exhibit desirable traits. This technique was applied to selectively breed plants to produce larger fruits, bigger yields and so on.

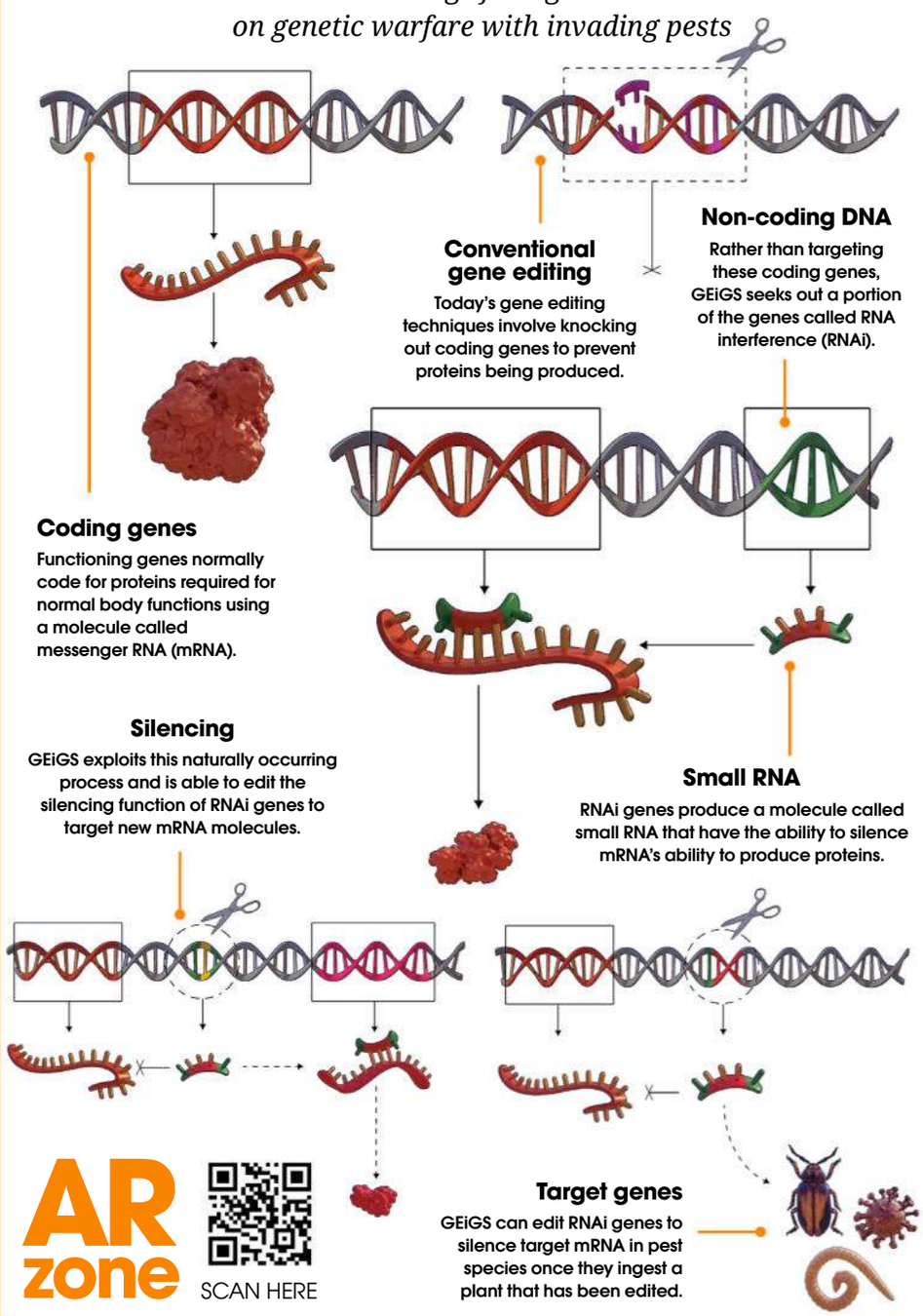
Today, a new technique is emerging that could give plants the ability to repel pests without having to insert foreign genes. Known as Genome Editing induced Gene Silencing (GEiGS), UK-based biotechnology company Tropic Biosciences has created a novel approach to genetically altering crops to keep pests at bay.

GEiGS is a technology that can edit a sequence of genes that code for a molecule that can silence the function of other genes. Genes are like the blueprints of an organism, and their codes produce proteins that build and make the organism. If the production of these proteins is then turned off, that can cause the body to cease function and die. This is what GEiGS can exploit when dealing with invading pests.

Modified seeds might be able to fight off pests on their own

DNA knockout

How GEiGS can change food genetics to embark on genetic warfare with invading pests



© Illustration by Nicholas Forder

Did you know?
94 per cent of soybeans grown in the US are the result of genetic engineering

Around 92 per cent of corn in the US is genetically engineered

Pests and pesticides can both ruin a good crop

Death by genetics

Tropic Biosciences chief science officer Dr Eyal Maori tells us how GEiGS is applied in the real world and how it could be used in the future

© Tropicol Biosciences

How does GEiGS work?
The core principle of GEiGS is that we map all these RNAi genes, through minimalistic gene editing, changing maybe five to a max of 20 nucleotides. We redirect [them] to seek and destroy like smart missiles. Smart missiles have coordinates and explosive powers, so GEiGS is about changing the coordinates and keeping the explosiveness. We redirect the seek recognition of this molecule from one target to any target of choice. For example, we take an RNAi gene and we now target a nematode gene instead of other genes. Now you can redirect these RNAi genes against other genes within the plant cell to fight against a virus, fungus or any other pests.

How do RNAi molecules work against insect pests?
Ten years ago, we thought that this seek-and-destroy mechanism works only inside cells. Before it was thought that this RNAi mechanism targets only intracellular parasites such as viruses. Then we learned that the RNAi molecules can move between cells. Then they can protect cells from a distance from the original cells that produce this RNAi molecule. Later on, we found out these molecules can move not just between cells, but can move between organisms. So RNAi can be produced in one organism and can silence and target genes in a different organism. This is how it relates to the pest-control strategy. You can produce molecules in a plant that can recognise nematode – a parasitic worm – genes. The nematode is fed on the plant cells that produce the RNAi molecules. These RNAi molecules are taken up from the digestive system of the nematode and then they are spread all over the nematode's body and they are taken up by the nematode cells.

Within the nematode's cells these RNAi molecules know how to recognise nematode genes that are very important for the vitality of the nematodes. When they recognise these genes they target them, they destroy them and then the nematode dies.

So it's like a genetic poison?
In a way, but I wouldn't use the word poison. It's genetic warfare between host and parasite. What we have learned in the last three to four years is that plants produce natural small RNA that can target fungal agents. Apparently, this transfer and communication of RNAi molecules have evolved as an immune mechanism of plants against a fungus. Also, it was discovered that fungus produces small RNA that is transferred to the plant to shut down the immune system of the plant. It's a genetic warfare, or arms race, between host and pathogen. It's this transfer of genetic information that is absolutely amazing; it's mind-blowing.

> **"It's a genetic warfare, or arms race, between host and pathogen"**

Does GEiGS affect the function of the plant species that's been edited?
Essentially not, because there are quite a few copies of the non-coding gene that we edit. We edit only some of them or even only one of them and we redirect its specificity and activity against, let's say, the nematode. The other copies still maintain a natural role. Essentially, we just gained new protection and gained a function, while keeping the natural function intact.

What are the future applications of GEiGS?
GEiGS could be applied to diverse hosts – plants and animals, including aquaculture and livestock. Also, you could apply GEiGS to enhance the performance of crops or livestock. It's not just about protection, but also, for example, to increase yield and to promote resistance to droughts.

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UNDERSTANDING Genetics

Future PLC Quay House, The Ambury, Bath, BA1 1UA

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Head of Print Licensing **Rachel Shaw**
licensing@futurenet.com
www.futurecontenthub.com

Circulation
Head of Newstrade **Tim Mathers**

Production
Head of Production **Mark Constance**
Production Project Manager **Matthew Eglinton**
Advertising Production Manager **Joanne Crosby**
Digital Editions Controller **Jason Hudson**
Production Managers **Keely Miller, Nola Cokely, Vivienne Calvert, Fran Twentyman**

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For enquiries, please email: mfcommunications@futurenet.com

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